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Multi-agent coordination techniques for naval tactical combat resources management

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Defence R&D Canada – Valcartier

Technical Report

DRDC Valcartier TR 2006-784

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Abstract

Reaction times of modern current and future war platforms are eroded, since they are expected to operate in a large variety of complex scenarios. To cope with the increasingly diverse air and surface threats, modern platforms, either operating in a single ship configuration or within a (joint and/or combined) task group/force, will require their sensor suite and weapon arsenal to be efficiently managed. The coordination and tight integration of these resources will also be required.

The Decision Support Systems (DSS) Section, at Defence Research & Development Canada – Valcartier (DRDC Valcartier), has initiated collaboration with industry and university partners. This collaboration aims at developing and demonstrating advanced concepts of combat resource management, which could apply to the current Command & Control Systems (CCSs) of the Halifax and Iroquois Class ships, as well as their possible future upgrade (*e.g.*, Canadian Surface Combatant platform), in order to improve their performance against the predicted future threat. This activity builds upon and broadens the scope of prior research in the domain. It is oriented to the study, development, and implementation of management decision aids for tactical shipboard resources, based on intelligent agent technology and techniques for multi-agent planning and coordination.

This report presents a review of agent and multi-agent coordination approaches. Theoretical basis of distributed planning in multi-agent systems is introduced and coordination mechanisms are described. Multi-agent approaches are used to address the coordination problems for: 1) hardkill/softkill, 2) weapons deployment/ship navigation, and 3) multi-ship positioning and operations. Results of the implementation and test of different algorithms for these combat resource coordination problems, in naval engagements, are presented and discussed.

Résumé

Étant donné la complexité et la grande diversité des scénarios dans lesquels les plates-formes militaires modernes doivent évoluer, leur temps de réaction se voit rétrécir continuellement. Ainsi, pour faire face aux menaces aériennes et de surface de plus en plus diverses, ces plates-formes, qu'elles fassent partie d'une force inter-armée ou de coalition, doivent absolument compter sur une gestion efficace de leurs arsenal d'armes et de leurs capteurs. La coordination et l'intégration de ces deux types de ressources sont également requises.

La Section des systèmes d'aide à la décision (SAD) de Recherche et développement pour la défense Canada – Valcartier (RDDC Valcartier) a mené à terme une collaboration avec des partenaires de l'industrie et du milieu universitaire. Cette collaboration a comme principal objectif le développement et la démonstration des concepts avancés de la gestion de ressources afin d'améliorer l'efficacité défensive des plates-formes face aux menaces prévisibles. Ces concepts pourraient s'appliquer aux systèmes de Commandement et Contrôle (C2) actuels à bord de navires canadiens des classes Halifax et Iroquois, ainsi qu'à leurs versions

futures (exemple, *Canadian Surface Combatant*). Cette collaboration poursuit et élargit la portée de travaux antérieurs dans le domaine. Elle vise à étudier, développer et implanter des outils d'aide à la décision pour aborder le problème de la gestion des ressources tactiques embarquées. Ce travail se base sur la technologie des agents intelligents et les techniques de planification et de coordination multi-agents.

Ce rapport présente une revue de différentes approches de coordination pour les systèmes multi-agents. Les fondements théoriques et les problèmes de planification distribuée dans un contexte multi-agent sont exposés. Par la suite, ces approches multi-agents sont appliquées aux problèmes de : 1) la coordination de ressources de destruction ('hardkill') et de ressources de mise hors de combat ('softkill') ; 2) la coordination du déploiement des armes et de la navigation du navire et 3) la coordination du positionnement des navires et des engagements, dans le cas de plusieurs navires. Les résultats de l'implantation et de l'expérimentation des différents algorithmes pour coordonner les ressources de combat dans les engagements navals sont présentés et discutés.

Executive summary

Multi-agent coordination techniques for naval tactical combat resources management

A. Benaskeur
É. Bossé, D. Blodgett; DRDC Valcartier TR 2006–784; Defence R&D Canada – Valcartier; July 2008.

Management of tactical combat resources, as a part of military naval Command & Control (C2) process, provides a real world multi-agent application where the agents are both human and software decisionmakers. Naval platforms, such as Halifax Class Frigates, use different modules that interact together to defend themselves and it is necessary to propose ways to optimize the allocation and the coordination of the different resources and agents in order to increase the ship's defensive effectiveness, and reaction time, against threats.

In recent years, intelligent agent and multi-agent theoretical concepts and technology have become more and more important in many fields. The simple agent technology aims at conceiving entities capable of acting in a rational way. However, in many applications, the agent alone is insufficient to perform all the tasks, and it is preferable to view it evolving with other agents. This defines a Multi-Agent System (MAS), where agents interact together in order to plan, cooperate, compete or more simply coexist.

One specific interest in the reported work turns around the development, implementation, use of multi-agent coordination and cooperation. Multi-agent systems are explored with, as main goal, the conception of a combat resource management system for a generic military warship that could ultimately be extended to the Halifax and Iroquois Class ships, as well as to the future Canadian Surface Combatant (CSC) platform. This report investigates more specifically the coordination approaches. Several advanced techniques were implemented and compared, and their respective advantages and disadvantages discussed. These techniques include a Central Coordinator, a WhiteBoard, and a Mediator. The target application was the coordination of Anti-Air Warfare (AAW) hardkill and softkill resource. It was concluded that the Central Coordinator technique should be the most effective. A test bed environment was developed to investigate the different algorithms for tactical combat resource coordination. The developed Naval Display Simulator (NDS) uses JACK™Agent development tool.

A second important aspect of the reported work concerns the coordination of weapons deployment and positioning. Since the effectiveness of a particular weapon varies depending on the orientation of the ownship with respect to the threats faced, a key element of the coordination process is to manoeuvre the ship to most effectively use all the combat resources. It was shown that the environment surrounding the ownship could be divided into fundamental sectors for weapons deployment. The method to determine the general effectiveness of each sector for the threats faced is described, and a coordination technique that exploits this knowledge to optimally position the ownship is proposed. It is demonstrated that using the ship positioning coordination improves the defence plan efficiency.

Finally, preliminary investigations were also made to consider distributed planning in multi-agent systems in order to extend coordination techniques of combat resources to multiple platforms configurations. In this context, an approach is proposed to tackle the coordination problem under bandwidth constraints, while using mobile agent technology.

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Multi-agent coordination techniques for naval tactical combat resources management

A. Benaskeur
É. Bossé, D. Blodgett ; DRDC Valcartier TR 2006–784 ; Recherche et Développement pour la Défence Canada – Valcartier ; juillet 2008.

La gestion des ressources tactiques fait partie du processus du commandement et contrôle (C^2) naval militaire. Elle fournit une application à caractère multi-agent, où les agents sont des décideurs humains ou des agents logiciels. Pour se défendre, une frégate de classe Halifax utilise différents modules qui interagissent ensemble. Afin de maximiser l'efficacité des capacités défensives de la frégate face aux menaces, on requiert une optimisation de l'allocation et de la coordination de ses différentes ressources et agents, en particulier quant au temps de réaction.

Les technologies d'agents intelligents et de systèmes multi-agents ainsi que les concepts théoriques sous-jacents sont de plus en plus présentes dans plusieurs domaines. La technologie agent vise à concevoir des entités capables d'agir rationnellement. Toutefois, dans beaucoup d'applications, un agent seul est incapable de réaliser toutes les tâches requises. Il est alors préférable de le voir évoluer avec d'autres agents. Cela définit un système multi-agent dans lequel l'interaction entre les agents permet la planification, la coopération, la compétition ou, tout simplement, la coexistence.

Un aspect du travail rapporté dans ce document s'intéresse spécifiquement, en plus du développement et l'implantation, à l'utilisation de la coopération et de la coordination multi-agents. Les systèmes multi-agents sont envisagés dans la perspective de concevoir un système de gestion des ressources de combat pour un navire de guerre. L'utilisation de ce système générique pourra ensuite être étendue aussi bien aux navires de classe Halifax et Iroquois qu'à leurs futurs remplaçants, en l'occurrence la plate-forme *Canadian Surface Combatant* (CSC).

Ce rapport explore plus spécifiquement les problèmes de coordination. Différentes techniques avancées ont été implantées et comparées, et leurs avantages et désavantages respectifs discutés. Ces techniques comprennent : le *Central Coordinator*, un *WhiteBoard*, et un *Mediator*. L'application cible consiste à coordonner les ressources de destruction ('hardkill') et les ressources des mise hors de combat ('softkill') dans le but de contrer les menaces aériennes (AAW). On a conclu que la technique utilisant le *Central Coordinator* est la plus efficace.

Un banc d'essai baptisé *Naval Display Simulator* (NDS) a été développé. Il utilise l'outil logiciel de développement JACK$^{\text{TM}}$Agent et permet l'expérimentation des différents algorithmes de planification et de coordination des ressources tactiques de combat.

Ce rapport présente aussi les résultats des travaux sur la coordination du déploiement des

armes avec le positionnement du navire. Étant donné que l'efficacité d'une arme dépend grandement de l'orientation du navire par rapport aux menaces, un élément important dans le processus de coordination est de pouvoir manœuvrer le navire afin d'utiliser les armes disponibles à bord de la manière la plus efficace possible. On montre que l'espace entourant le navire peut être subdivisé en secteurs de base pour le déploiement des armes. Une méthode pour déterminer l'efficacité des différents secteurs face aux menaces est décrite. Par la suite, une méthode de coordination est proposée afin d'exploiter les résultats quant à l'efficacité des secteurs pour optimiser la position du navire. On montre que la coordination du positionnement du navire améliore l'efficacité des plans de défense.

En dernier, des résultats d'études préliminaires, concernant l'extension de la problématique de coordination multi-agent au cas de plusieurs navires, sont présentés. Une approche basée sur la technologie des agents mobiles est alors proposée pour résoudre le problème de la coordination sous les contraintes de bandes passantes.

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1 Introduction

Advances in threat technology, the increasing difficulty and diversity of open-ocean and littoral (*i.e.*, near land) scenarios, and the volume and imperfect nature of data to be processed under time-critical conditions pose significant challenges for future shipboard Command & Control System (CCS). Among other functionalities, a CCS provides capabilities to allow operators to evaluate the threat level of the different objects that are present within the Volume of Interest (VOI). When deemed necessary, the CCS uses the shipboard Combat Power (CP) to response to those threats. However, current operational systems generally provide little support for tactical decision making in complex, highly changing scenarios where time for decision making and action execution is at a premium. The need for such support is all the more pressing given the current emphasis on littoral warfare, where reduced reaction times and complex Rules of Engagement (ROE) are the norm.

Management of tactical shipboard CP, as a part of military naval Command and Control (C2) process, provides a real world application that involves both human and software decision-makers. To defend itself, a naval platform, such as a Halifax Class Frigate or Iroquois Class Destroyer, uses different systems and modules that interact directly or indirectly together. Therefore, it is necessary to propose ways to allocate and coordinate the use of the different systems in order to increase the ownship's defensive effectiveness against potential threats.

Defence Research & Development Canada – Valcartier (DRDC Valcartier) with its partners from Canadian universities and industry have, for several years now, been investigating methods to augment or enhance existing shipboard CCS capabilities. DRDC Valcartier was involved, among others, in a collaborative grant with Natural Sciences and Engineering Research Council of Canada (NSERC), Lockheed Martin Canada, Université Laval, and Université de Montréal to investigate, design, develop and implement a real-time Decision Support System (DSS). This DSS can be integrated into a ship's CCS to assist operators aboard in conducting the tasks related to the tactical C2 process, focusing on naval combat Resource Management (RM) in the context of Above Water Warfare (AWW). This collaboration built upon and broadened the scope of prior work [1] and aims at exploring concepts concerned with Multi-Agent System (MAS) for the design, development, implementation, and evaluation of a computer-based, real-time DSS to assist operators in conducting tactical C2 processes, with an emphasis on Combat Power Management (CPM).

To achieve the above stated primary goal, the following objectives were defined for the reported project:

1. To review and evaluate real-time planning and coordination mechanisms (multi-agent planning & scheduling) applied to AWW CPM problem [2].
2. To specify, develop, and validate planning and coordination techniques to enable one or more platforms in order to defend themselves in an efficient way against incoming threats. Coordination concerns both single-ship hardkill/softkill coordination and

multi-ship plan coordination. Also, the presented work considers the ship positioning as a resource that needs to be coordinated with the other resources.

3. To develop a simulation and testing capability and review its efficiency according to a software engineering approach.

Finally, the ultimate objective is the contribution to the development of methodological knowledge and skills for RM to meet the challenge of decision making in the context of naval tactical operations. This effort will allow the Department of National Defence (DND), the universities, and industry partners to acquire knowledge and expertise in this domain.

Most of the work presented in this report was achieved under the above-mentioned collaboration, whose one of major objectives is to explore concepts concerned with *agent* and *multi-agent* planning and coordination technology, with application to the tactical naval CPM for a Frigate-like platform. The focus on *agent* and MAS technology was motivated by the fact that, in the recent years, this technology has become more and more important in many fields such as computer engineering, industrial engineering, etc. Another reason that sustains the choice for the multi-agent techniques is that naval tactical CPM is a complex process, which involves distributed resources and decision making that require coordination and cooperation.

The work and results of this research effort are described in a series of two reports. The first [2] addressed agent-based planning aspects. The current one concerns coordination and cooperation issues in naval CPM problems.

1.1 Organisation of the report

Naval CPM problem is first introduced in Chapter 2, where some generic issues relative to military C2 systems are also discussed. Chapter 3 presents the distributed planning problems in a multi-agent context, with a focus on coordination techniques. Chapter 4 addresses the specific problem of coordinating hardkill (HK) and softkill (SK) combat power in naval operations. The problems of coordinating combat resources deployment with ownship positioning is discussed in Chapter 5. Chapter 6 introduces response coordination for multiple platforms. Chapter 7 provides report and project conclusions, including recommendations for future work. Appendix A describes the specifications of a Halifax Class-like frigate and its resources that were used for this project. Appendix B presents the simulator used to test the different defence planning strategies. The simulator has been implemented using Java and JACK™programming languages.

2 Naval combat power management

This chapter describes the Combat Power Management (CPM) process and the related problems from a military perspective and situates it within the broader scope of naval tactical Command and Control (C2). In particular, the focus here is on issues related to organisational forms and distributed decision architectures, which are precisely the areas that offer the most fertile ground for both basic and applied researches.

1. **C2 is a distributed environment** – Solving the C2 related problems involves both human and software decision makers. The latter may be geographically dispersed due to the operational environment, the nature and characteristics of the threat and/or the configuration and orientation of the ownship itself. All those contribute to the necessity of a distributed architecture of C2 systems. Cooperation, coordination, and communication between the decision makers are thus crucial in such a distributed architecture. The military C2 systems are often modeled as a multi-agent organization, within which the decision agents are both human and software decision makers.

2. **C2 has a functional architecture** – Another key element of the C2 process is its functional decomposition into a set of generally accepted C2 functions (see Figure 1) that must be executed in some reasonable delays to ensure mission success. A list that gives a very high-level description of those functions, related to defensive battle management problem, is given below.

   (a) **Surveillance** - It includes *object detection*, *object tracking*, and *object identification* tasks or functions. Object detection is very depending on the performance of the used sensors. Object tracking uses the sensor data to optimally estimate the current kinematical properties of the object, and then predict its future positions. Object identification (and classification) assesses the identity and the class of objects. This also results in the resolution of true objects from decoys or non-hostile objects.

   (b) **Threat Evaluation** - It establishes the intent and the capability of all non-friendly entities within the Volume of Interest (VOI). It refers to the ongoing process of determining if an entity intends to inflict evil, injury, or damage to the defending forces and their interests, along with the ranking of such entities according to the level of threat they pose.

   (c) **Engageability Assessment** - It concerns the evaluation of own-force's engagement options and their feasibility against all non-friendly entities within the VOI. This process is intended to help the weapons assignment process by eliminating candidate solutions that violate one or more hard constraints, and will therefore not be feasible. Several aspects can be taken into consideration during this process, such as Rules of Engagement (ROE), blind zones, ammunition availability, etc.

   (d) **Weapons Assignment** - In this process, decisions are made on how to deal with the identified threats. This process can be subdivided into several sub-problems that include mainly the following three ones:

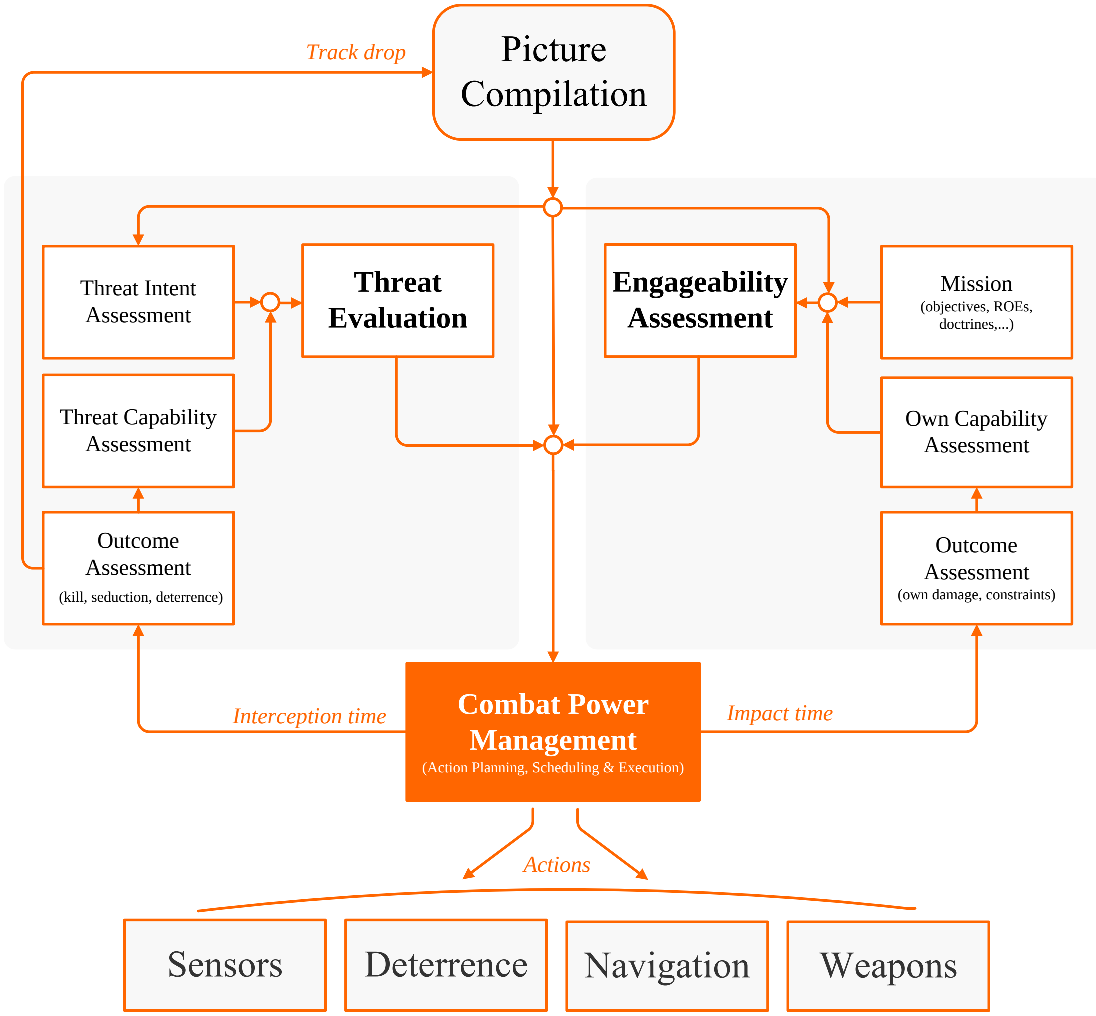

Figure 1: *C2 functional decomposition*

i. **Response Planning** - This includes the combat resource *allocation*[1] and the combat resource *coordination/cooperation*[2]. During the combat resource allocation, one or more weapons are assigned to engage each threat, including the assignment of supporting resources (as sensors, communications, etc.) required for each and every one-to-one engagement. Combat resource coordination is about conflict (negative interaction) resolution, while combat resource cooperation is about synergy (positive interaction) exploitation.

ii. **Response Execution** - This is the process by which the planned response is executed in real-time. This also includes the execution monitoring functionality. Since the responses are executed in a dynamic environment, subject

[1] The problem of combat resource allocation is outside the scope of this report and is treated in detail in [2].

[2] Which is the core problem addressed in this report.

to uncertainty and changing goals and conditions, the actual execution contexts will be different from the projected ones (the ones that motivated the construction of the original response). Monitoring is required to help detect, identify, and handle contingencies caused by uncertainty and changing nature of the environment.

iii. **Outcome Assessment** - The process by which the outcome (ownship damage, or threat damage/kill) of the executed actions is evaluated.

This process necessitates a highly dynamic flow of information and decision making that involves a number of operators and sophisticated support capabilities.

3. **C2 is a complex process** – The AWW problem is a very complex problem, and this complexity often rises from the multitude, the heterogeneity and the inter-relationships of the resources involved. This is in general the case when simultaneous engagements involving heterogeneous sensor and/or weapon systems can take place, and human commanders make a large part of the decisions. Generally, no commander alone can deal with the inherent complexity of the entire engagement; this leads to a decomposition of the decision process along distinct expertise or know-how dimensions. In the light of these considerations, team training is essential, in a C2 organisation, so as to achieve superior coordination and to make the best utilisation of scarce common resources. Moreover, a military CCS must take into account the specific command and decision established hierarchy.

4. **C2 deals with large volumes of data under stringent time constraints** – Perceptual and cognitive processing is complicated by the fact that the information is derived from a variety of organic and non-organic sources. Those sources include radar, Electronic Support Measures (ESM), Infra-Red Search and Track (IRST), Identification Friend or Foe (IFF) transponder responses, as well as intelligence information from shore and various deployed units. Particular processing problems are caused by the fact that: i) non-organic information is generally less timely than organic information, what makes it difficult to correlate the two types of information; and ii) the data to be integrated are generally imperfect[3]. It follows that operators may have to handle potentially large situation uncertainties and at any given moment there may be several likely interpretations of the tactical picture. This leads to processing large volumes of data under stringent time constraints.

2.1 Properties of the combat resource management problem

As part of the naval C2, the CPM problem is subject to a number of properties and constraints, inherent to the very nature of RM problems in dynamic environment, generally, or imposed by the military and naval context. The following are few of the most relevant [3] properties of the CPM problem that should be taken into consideration in developing management capabilities.

[3] It can be uncertain, incomplete, imprecise, inconsistent, or ambiguous, or some combination of these, due to limited sensor coverage, report ambiguities, report conflicts, or inaccuracies in measured data.

1. **Deterministic vs. Stochastic** – If the next state of the environment is completely determined by the current state and the action to be executed by the decision maker or the planner, then the environment is said to be deterministic; otherwise, it is stochastic by nature. The CPM problem is very stochastic: the manager cannot exactly predict the evolution of the environment according to the current state (for example: new threats emerging, threat trajectory changing, own resource performance, etc.).

2. **Episodic vs. Sequential** – In an episodic environment, the decision making problem is divided into atomic episodes. Each episode consists in perceiving and then performing a single action. Crucially, the action selection process in a given episode does not depend on the actions taken in previous episodes. Therefore, the choice of actions in each episode depends only on the episode itself. In sequential problems, the current decision could affect all future decisions. The CPM problem is sequential in the sense that making any decision can affect and constraint subsequent decisions (*e.g.*, committing a given resource against a given threat can have an impact on the availability of that resource for subsequent engagements). Sequential problems are much harder than episodic ones, because the decision making process needs to think ahead in future about consequences of current decisions and actions. For simplification, sequential problems are often treated as episodic. Under severe time constraints, this may lead to very undesirable results.

3. **Static vs. Dynamic** – If the environment may change during the decision making process, then the environment is said to be dynamic; otherwise, it is static. Static environments are easy to deal with because the decision making process does need to worry about time. However, time is a central concern when dealing with dynamic environments. Continuous action is required to cope with changes in the environment. The CPM problem may take the two forms:

   (a) In the static version of the CPM problem, all the inputs to the problem are fixed; that is, all targets are known, all weapons are known, and all weapons engage targets in a single stage. This concerns mainly the off-line planning for tactics generation.

   (b) The dynamic version of the CPM problem is a multi-stage problem where the environment may change very quickly and very often (*e.g.*, threats keep moving, manoeuvring, appearing, disappearing, etc.) during the response planning process. Also, in the dynamic version, when some weapons engage the targets at a given stage, the outcome of this engagement is first assessed, and a strategy for the next stage is then decided. This is called a "shoot-look-shoot" strategy since the defence is alternating between shooting the weapons and observing (assessing) the outcomes. In such a context, the reaction time (to the environment changes) becomes the main issue. It is almost always possible to find an optimal response to a given situation. However, the issue remains to provide it on time. This is why, in very dynamic environments, optimal responses are seldom achievable. The enormous combinatorial complexity of the problem implies that, even with the supercomputers available today, optimal solutions cannot be obtained

in real time. Rather, what are sought after are satisfying responses; that is the best ones given the constraints.

4. **Single vs. Multi-Criteria** – If the decisions to be made are evaluated according to a single criterion, the problem is said to be single-criterion, otherwise it is said to be multi-criteria. In the latter case, that represents most of real life problems, decisions are evaluated on the base of several criteria that may be in conflict with each other. Examples for naval CPM include the threat level, the own resources effectiveness, and a cost of actions.

In summary, the CPM problem is a distributed, stochastic, sequential, dynamic, and multi-criteria one. The project ultimate goal is to allocate, coordinate, and schedule the use of the shipboard combat resources over a time horizon that provides for and optimizes single ship/point defence, as a primary objective, and ultimately multi-ship/area defence capabilities. Note that the ship has, as described in the next chapter, a set of tactical resources that allows it to defend itself.

2.2 Shipboard combat resources

The exact nature of the specifications and capabilities of the various Anti-Air Warfare (AAW) weapons on the Canadian warships is obviously very complex, and much of that information is classified by the Department of National Defence (DND). To avoid this issue, and in order to maintain emphasis on the research interests and not be burdened by the complexity and fidelity of the representation, a considerably simplified model of the relevant AAW weapons was used for this project, as reported here. This model is a simple, non-classified version of AAW weapons for a typical frigate. The results could eventually be applied to the Canadian warships of Halifax class, to some extend to the Iroquois class, given that the latter shares to same layered defence configuration with the former.

The following subsections give a brief description of the combat resource available on a typical frigate. More details can be found in Appendix A.

2.2.1 Hardkill resources

The AAW hardkill (HK) are weapons that are directed to intercept a threat and actively destroy it through direct impact or explosive detonation in its proximity. The range of different types of HK weapons varies, and the effectiveness of these weapons depends on a variety of factors[4]. The AAW HK weapons for a typical frigate include Surface-to-Air Missile (SAM) systems that have the greatest range, an intermediate range Gun, and a Close-In Weapon Systems (CIWS) that is a short-range, rapid-fire gun. Closely allied to these weapons are two Separate Tracking and Illuminating Radars (STIRs) that are used to guide a SAM to a threat, and to point the Gun. This effectively provides two concurrent fire channels for the AAW HK weapons. The CIWS has its own pointing radar.

[4] *E.g.*, the distance to the threat, the type of threat, the speed of the threat, the environment conditions, etc.

2.2.2 Softkill combat resources

The AAW softkill (SK) weapons use techniques to deceive or disorient a threat to cause the threat to destroy itself, or at least lose its fix on its intended victim. Again, the range and effectiveness of these weapons vary considerably. The AAW SK weapons for a typical Canadian frigate include Chaff and Jamming systems. The Chaff system launches a shell that produces a burst at a designated position. The resultant Chaff cloud has a significant radar cross-section that can be used to screen the ship or produce an alternate target on which a radar-guided threat can fix. The Jamming system uses electromagnetic emissions to confuse the threat's sensors, then causing the threat to either lose its fix on its intended target, or to improperly assess the position of its target.

During an attack, Jamming and Chaff systems must act concurrently and in a complementary way. First, the Jammer is used to break the missile threat's radar lock on ownship. Once the missile has lost its target, the Jammer creates a false target position on the missile's radar. Then Chaff is deployed at a position consistent with the false one provided by the Jammer. In this way, the missile's radar locks onto the Chaff cloud as its new target.

Note that, due to their different mechanisms, the HK and SK weapons have historically led independent existences in terms of design and operational deployment. Generally, these weapons are supervised by separate control personnel. Thus, the complex task of optimally combining the two types of weapons falls squarely on the shoulders of the person responsible for overall air defence. The inherent differences between HK and SK weapons, and the nature of their deployment history on typical warships, lead naturally to a representation of them as being two software agents, so that each determines a real-time plan for its resources and both have to coordinate plans between them.

2.2.3 Sensors

As a part of the tactical combat resources, the ship has two classes of sensors: surveillance and fire support. For the surveillance, the ship possesses two sensor systems:

AN/SPS-49 – which is an L-band, long-range, two-dimensional, air-search radar system that provides automatic detection and reporting of targets within its spatial VOI. The AN/SPS-49 is used for early target detection.

SG-150 – which is the multi-purpose air and surface search naval radar developed by Ericsson.

The Halifax Class Frigate combat resources comprise two Fire Control Radar (FCR) systems called respectively STIR-A and STIR-B. STIR-A is installed on the roof of the bridge and STIR-B on the raised radar platform immediately forward of the helicopter hangar. The STIRs are responsible for the control of the SAM fire channels and the Gun. They provide the SAM and the Gun weapon systems with fire control quality track data for engagement calculations.

Sensors, for both surveillance and fire support, need to be coordinated with the deployment of weapons in order that maximize the defence effectiveness.

2.2.4 Ship navigation

The position and the manoeuvres of the ship play a key role in the ship's defensive plan. Therefore, the ship navigation is treated as combat resource that needs to be coordinated with the other combat resources as deployed, in order to increase the ship's survivability (see Chapter 5 for more details).

In this report, the focus is on the Weapons Assignment, and more particularly on the combat resource coordination and cooperation problems. The combat resource allocation planning problem is treated in the companion report [2].

2.3 Resource coordination/cooperation problem

Given the different nature of the existing weapons, the effectiveness of a defensive plan depends on all the involved weapons, as well as the environment and threat properties. Even though, the optimality of the partial plans [2] (*e.g.*, HK plan and SK plan) is assumed, there still be coordination/cooperation problems that need to be solved in order to guarantee the viability and effectiveness of the entire engagement. These problems are inherent to distributed environments and concern interactions within the decentralized problem solving process. Examples of common types of interactions include:

1. Cooperation - This defines joint operation or action, that is, the process of working together toward a common goal; sharing effort, expertise, and resources to achieve some mutually desirable outcome.
2. Coordination - This is the process of managing interactions and dependencies between activities. With strictly independent activities, where there is no interaction or dependency, there is obviously no need of coordination. Therefore, coordination can be viewed as a regulation process of diverse interacting and/or inter-dependent tasks within an integrated operation. The interaction and the dependency are seldom direct, but through shared resources, which act as constraints on the different activities. This is why most of coordination problems can be viewed as Constraint Satisfaction Problems (CSP).
3. Negotiation - coming to an agreement, which is acceptable to all the parties involved.

In naval context, these interaction problems may occur on-board a single ship, as well as within a set of cooperating platforms (*e.g.*, Task Group, Coalition, etc.). Below are examples of interaction between HK and SK weapons that may require some sort of coordination and cooperation.

2.3.1 Hardkill/softkill interaction

It is possible to observe different interactions between the weapons [4, 5] of a single platform. These interactions may be positive (+, to be re-enforced), negative (−, to be removed, or at least minimized), or simply neutral (∘). Examples of such interactions are listed below.

+ **Jamming & Chaff** — An example of positive interaction is given by the combination of Jamming and Chaff, also known as *Damping.* If, the probability of success for the Chaff alone on a threat is p_1, and for the Jamming is p_2, then the use of the two together gives an efficiency p_3 such as

$$1 - p_3 < (1 - p_1)(1 - p_2) \tag{1}$$

  This efficiency is superior to using the two weapons separately. So there is a synergy between the two weapons. What happens is that the Jamming spoofs the Ant-Ship Missile (ASM) to a position (range pull-off) consistent with a Chaff already deployed, which is more persuasive than either Jamming or Chaff used alone.

+ **SAM & Jamming** — Jamming steadies ASM trajectory (no ship glint) as it enters the "home-on-jam" mode, thereby increasing the probability of a kill by the SAM. This enhances the chance of survival for the ship because the SAM has a steadier target to intercept.

∘ **Chaff & SAM** — If an ASM attacks at an angle of 45°, with no need to turn the ship for optimum HK/SK deployment, both Chaff seduction and SAM can be used advantageously. Their engagement cycles however end at different times. This is the case because SAM interception, in general, occurs before the Chaff break-lock moment. If the SAM succeeds in destroying the incoming ASM, then Chaff seduction is no longer necessary, although it still acts as a safeguard in case either the SAM fails, or there are more ASMs. This result would be degraded if the ship was turned to maximize either HK or SK performance, since such action would shift the weapon pair to another region. However, status remains "neutral no interaction". Such actions are not so unreasonable. If within a pair, one weapon has a poor performance, the operator may drop it in order to make the second more effective.

∘ **Chaff & SAM** — If while making a Chaff seduction more effective, the ship is turned to offer its minimum Radar Cross-Section (RCS) to the ASM, the move may put the SAM fire channel into a blind arc (see Chapter 5 for more discussion on ownship positioning). Such an unusual tactic would presumably only be used if there are no more SAMs left to fire.

− **SAM & Jamming** — When the Jamming changes the direction of an incoming ASM, the SAM has more chance of missing the ASM. So the probability of a kill for the SAM might be diminished. This interaction is disputable because it can be supposed that if the Jamming has caused the path of the ASM to deviate, the ASM will not hit the ownship independently of what the SAM will do. But as noticed earlier, these two weapons have a positive interaction too. Thus the Jamming may guide the SAM as the ASM changes of direction.

- **SAM & SAM** — If two SAMs are fired against two different threats that are near each other, it is possible that one SAM could be attacked by the other and vice-versa. The metal of SAM causes this attraction. This effect diminishes the chances for both threats to be destroyed by the SAMs.
- **CIWS & Chaff** — When a Chaff is deployed in order to destroy a threat that is in the same direction as a firing CIWS, the CIWS may have its efficiency largely diminished. In fact, the CIWS's bullets may be deviated or obstructed by the Chaff in action.
- **Chaff & HK** — When a STIR or a CIWS radar is trying to guide a HK weapon through a Chaff, its range might be greatly diminished. In fact, Chaff scrambles our radars.
- **SAM & HK** — If a SAM explodes at an unusual place[5], it can deviate the CIWS, the Gun, or a SAM already in action. The radars of these weapons will be attracted by this explosion.

Given the above list, the necessity of effectively coordinating HK and SK deployment plans becomes clear. Management of these interactions will help capitalize on positive interactions and avoid or, at least, reduce negative interactions. Three methods of coordination and the results of their application are presented in the next chapters.

[5] In a Chaff by example.

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3 Distributed planning in multi-agent systems

In many respects, distributed planning [6] can be thought of simply as a specialisation of distributed problem solving, where the problem being solved is to design a plan. But because of the particular features of planning problems, it is generally useful to consider techniques that are particularly suited for planning.

Distributed planning is something of an ambiguous term, because it is unclear exactly what is "distributed". It could be that the operative issue is that, as a consequence of planning, a plan is formulated that can be distributed among a variety of execution systems. Alternatively, the operative issue could be that the planning process should be distributed, whether or not the resulting plan(s) can be. Or perhaps both issues are of interest. In the sequel, it will be considered both distributed plans and distributed plan formation as options. Of course, the case where neither holds (since that is traditional centralized planning) will be skipped over (see [2] for more discussion on this aspect). Only the cases where one or both of these distributions exists will be considered. The focus is more on the integration process of partial plans because this is the main difference with the centralized planning. One must integrate partial plans to form a global plan to avoid negative interactions between them and to profit from the positive ones.

In the next three chapters, two different coordination techniques will be described. This concerns the **centralized planning for distributed plans** and the **distributed planning for distributed plans**. These methods are useful to coordinate the hardkill (HK) plan with the softkill (SK) plan for the naval Combat Power Management (CPM) problem.

3.1 Centralized planning for distributed plans

In centralized multi-agent planning [6], one agent called "the Central Coordinator" generates the global plan. In general, such a Central Coordinator has a global view of all the system and in this case, it:

1. can take in charge the identification of the interactions between the different activities of the different agents; and

2. resolves all conflicts before the execution of the global plan.

Plans that are to be executed in a distributed fashion can nonetheless be formulated in a centralized manner. For example, a partial order planner can generate plans that do not present a strict ordering between some actions, and where actions can be executed in parallel.

A centralized coordinator agent, with such a plan, can break it into separate threads, possibly with some synchronization actions. These separate plan pieces can be passed to agents that can execute them. If followed suitably, and under assumptions of correctness of knowledge and predictability of the world, the agents operating in parallel achieve a certain

state of the world consistent with the goals of the plan. Let us consider this process more algorithmically. It involves:

1. Given a goal description, a set of operators, and an initial state description, generate a partial order plan. When possible, bias the search to find a plan in which the steps have few ordering constraints among them.

2. Decompose the plan into sub-plans such that ordering relationships between steps tend to be concentrated within sub-plans and minimized across the different subplans [7].

3. Insert synchronisation (typically communication) actions into sub-plans.

4. Allocate sub-plans to agents using task-passing mechanisms. If failure, return to previous step(s) (decompose differently, or generate a different partial order plan, etc.). If successful, insert remaining bindings into sub-plans (such as binding names of agents to send synchronisation messages to).

5. Initiate plan execution, and optionally monitor progress (synthesize feedback from agents to ensure complete execution, for example).

The specific issues of decomposition and allocation that are involved in this sort of planning give it a special flavour. Essentially, the objective is to find, of all the possible plans that accomplish the goal, the plan that can be decomposed and distributed most effectively. But since the availability of agents for the sub-plans is not easy to determine without first having devised the sub-plans, it is not certain that the most decomposable and distributable plan can be allocated in any current context.

Moreover, the communication infrastructure capabilities can have a big impact on the degree to which plans should be decomposed and distributed. As an extreme, if the distributed plans require synchronisation and if communication channels are slow or undependable, then it might be better to form a more efficient centralized plan. The monetary and/or time costs of distributing and synchronizing plans should thus be taken into account. In practical terms, what this usually means is that there is some minimal sub-plan size beyond which it does not make sense to decompose a plan. In loosely coupled networks, this leads to systems with fewer agents, each accomplishing larger tasks, while in tightly connected (or even shared-memory) systems, communication and parallelism can be very demanding.

The most challenging version of distributed planning is when both planning process and its result are to be distributed. In this case, it might be unnecessary to ever have a multi-agent plan represented in its entirety anywhere in the system. And yet, the distributed pieces of the plan should be compatible, what at a minimum means that the agents should not conflict with each other when executing the plans. Preferably, agents should help each other achieve their plans when it would be rational to do so (*e.g.*, when a helping agent is no worse off for its efforts). The literature on this kind of distributed planning is relatively rich and varied. In the next section, the Partial Global Planning (PGP) technique [8, 9] will be presented.

3.2 Partial global planning

Partial Global Planning (PGP) fills a distributed planning niche and is particularly suited for applications where some uncoordinated activity can be tolerated and overcome since the agents are individually revisiting their plans midstream. As such, the system as a whole might at times (or even through the whole task episode) never settle down into a stable collection of local plans. PGP focuses on dynamically revising plans in cost-effective ways given an uncertain world, rather than on optimizing plans for static and predictable environments. It works well for many tasks, but could be inappropriate for domains such as CPM where guarantees about coordination must be made prior to any execution.

3.2.1 Task decomposition

PGP starts with the premise that tasks are inherently decomposed, or at least decomposable. Therefore, unlike planning techniques that assume that the overall task to be planned for is known by one agent[6], PGP assumes that an agent with a task to plan for might be unaware at the outset as to what tasks (if any) other agents might be planning for, and how (and whether) those tasks might be related to its own (as in the distributed vehicle monitoring, for example)[7]. As a fundamental assumption in PGP is that no individual agent might be aware of the global task or state, thus the purpose of coordination is to allow agents to develop sufficient awareness to accomplish their tasks nonetheless.

3.2.2 Local plan formulation

Before an agent can coordinate with others using PGP, it must first develop an understanding of what goals it is trying to achieve and what actions it is likely to take in order to achieve them. Hence, purely Partly agents [2], which cannot explicitly represent goals that they are trying to achieve and actions to achieve them, cannot gainfully employ PGP (or, for that matter, distributed planning at all). Moreover, since most agents will be concurrently concerned with multiple goals (or at least will be able to identify several achievable outcomes that would satisfy a desired goal), local plans will most often be uncertain. That is because it involves branches of alternative actions depending on the results of previous actions and changes in the environmental context while carrying out the plan.

3.2.3 Local plan abstraction

Since it is important for an agent to identify alternative courses of action for achieving the same goal in an unpredictable world, the details of these alternatives might be unnecessary given the agent's ability to coordinate with others. That is, an agent has to commit to activities at one level of detail[8] without committing to activities at more detailed levels[9]. Abstraction plays a key role in coordination; since coordination that is both correct and

[6] Which then decomposes the task into subtasks, which themselves might be decomposed, and so on.

[7] An application in which geographically distributed sensors cooperatively map the movements of vehicles across their sensed region.

[8] To supply a result by a particular time.

[9] Specifying how the result will be constructed over time.

computationally efficient requires that agents have models of themselves and others that are only detailed enough to gainfully enhance collective performance. In PGP, for example, agents are designed to identify their major plan steps that could be of interest to other agents.

3.2.4 Communication

Since coordination through PGP requires agents to identify how they could and should work together, they must somehow communicate their abstract local plans so as to build models of joint activity. In PGP, the knowledge to guide this communication is contained in the *Meta-Level Organisation* (MLO). MLO specifies information and control flows among the agents: who needs to know the plans of a particular agent, and who has authority to impose new plans on an agent based on having a more global view. The declarative MLO provides a flexible means for controlling the process of coordination.

3.2.5 Partial global goal identification

Due to the inherent decomposition of tasks among agents, the exchange of local plans (and their associated goals) gives agents an opportunity to identify when the goals of one or more agents could be considered sub-goals of a single global goal. Because, at any given time, the agent may know only portions of the global goal, it is called a partial global goal. Construction of partial global goals is, in fact, an interpretation problem, with a set of operators that attempt to generate an overall interpretation (global goal) that would explain the component data (local goals). The kinds of knowledge needed here are abstractions of the knowledge needed to synthesize results of the distributed tasks.

3.2.6 Partial global plan construction and evaluation

Local plans that can be seen as contributing to a single partial global goal can be integrated into a partial global plan, which captures the planned concurrent activities (at the abstract plan step level) of the individuals. By analyzing these activities, an agent that has constructed a partial global plan can identify opportunities for improved coordination. In particular, the coordination relationships emphasized in PGP technique uses a simple hill-climbing algorithm, coupled with an evaluation function on ordered actions, to search for an improved (although not necessary optimal) set of concurrent actions for the PGP plan (see Algorithm 1). The evaluation function sums evaluations of each action, where the evaluation of an action is based on features such as whether the task is unlikely to have been accomplished already by another agent, how long it is expected to take, and on how useful its results will be to others in performing their tasks.

3.2.7 Communication planning

After reordering the major local plan steps of the participating agents so as to yield a more coordinated plan, an agent must next consider what interactions should take place between agents. In PGP, interactions in the form of communicating the results of tasks are also

Algorithm 1 The algorithm for PGP plan step recording

```
Function PLAN-STEP-RECORDING(current ordering)
For the current ordering, rate the individual actions and sum the ratings
for each action do
  examine the later actions for the same agent and find the most highly rated one
  if the action is higher rated then
    swap the actions
  end if
end for
if the new ordering is more highly rated than the current one then
  replace the current ordering with the new one and go to step 2
end if
return the current ordering
```

planned. By examining the partial global plan, an agent can determine when one agent could be of interest to another agent, and can explicitly plan the communication action to transmit the result that will complete a task. If results need to be synthesized, an agent using PGP will construct a tree of exchanges such that, at the root of the tree, partially synthesized results will be at the same agent, which can then construct the complete result (see Algorithm 2).

Algorithm 2 The algorithm for planning communication actions

```
Function PLANNING-COMMUNICATION(partial task)
Initialize the set of partial task results to integrate.
while the set contains more than one element do
      for each pair of elements do
        find the agent that can combine the pair at the earliest time
      end for
      for the pair that can be combined earliest do
        add a new element (partial task) to the set of partial results for the combination and
        remove the two elements that were combined
      end for
end while
return the single element in the set
```

3.2.8 Acting on partial global plans

Once a partial global plan has been constructed and the concurrent local and communicative actions have been ordered, the collective activities of the agents have been planned. What remains is for these activities to be translated back to the local level so that they can be carried out. In PGP, an agent responds to a change in its partial global plans by modifying the abstract representation of its local plans accordingly. In turn, when choosing its next local action, an agent uses this modified representation, and thus the choice of local actions

is guided by the abstract local plan, which in turn represents the local component of the planned collective activity.

3.2.9 Ongoing modification

As agents pursue their plans, actions or events in the environment, that might lead to changes in tasks or in choices of actions to accomplish tasks. Sometimes, these changes are so minor that they leave the abstract local plan unchanged as used for coordination. At other times, they do cause changes. A challenge in coordination is to decide when the changes in local plans are significant enough to warrant communication and re-coordination. The danger in being too insensitive to changes is that an agent that informs others of minor changes can cause a chain reaction of minor changes, where the slight improvement in coordination is more than offset by the effort spent in getting it. On the other hand, being too insensitive can lead to very poor performance, as agent's local activities do not mesh well because each is expecting the other to act according to the partial global plan, which is not being followed closely anymore. In PGP, a system designer has the ability to specify parametrically the threshold that defines significant temporal deviation from planned activity.

3.2.10 Task reallocation

In some circumstances, the exogenous task decomposition and allocation might leave agents with disproportionate task loads. Through PGP, agents that exchange abstract models of their activities will be able to detect whether they are overburdened, and candidate agents that are under-burdened. By generating and proposing partial global plans that represent other agents taking over some of its tasks, an agent essentially suggests a contracting relationship among the agents. A recipient agent has an option of counter-proposing by returning a modified partial global plan, and the agents could engage in protracted negotiations. If successful, however, the negotiations will lead to task reallocation among agents, allowing PGP to be useful even in situations where tasks are quite centralized.

4 Hardkill/softkill coordination

Besides the purely planning and scheduling problem [2], there are several coordination and cooperation problems that need to be solved to make the engagement plan feasible. One of the main problems for single-ship configuration concerns the hardkill/softkill coordination and/or cooperation.

The inherent differences between hardkill (HK) and softkill (SK) weapon systems, and the nature of their deployment history on typical frigates, lead naturally to a representation of two parallel processes that each determines a real-time engagement plan. It is necessary to coordinate effectively both HK and SK plans.

The next step is to consider possible hardkill/softkill interactions (see §2.3.1). As stated by Malone and Crowston [10], coordination is generally viewed as the management of interactions. Dealing with HK/SK interactions is therefore a problem of coordination between the HK planning and the SK planning (each represented by a separate agent). When faced with one or several threats, these agents plan the use of the weapon resources of the ownship to counter the threat(s). In this context, tactical resource planning means allocating and scheduling the deployment of the ownship weapons against a set of threats with a precise time order. The HK and SK planning agents were implemented according to the simplified model as discussed above [2] (see §2.2).

As the HK and SK agents are independent planners, some interaction can occur between them. These planners are best considered as independent because, on current Canadian Frigates, they tend to operate in different systems. Thus, we need to coordinate these two agent planners, which should have the following capabilities.

- They should make *timely* responses in a changing world. This was the most critical consideration for our particular application.
- They should *react to changes* within the environment.
- They should exhibit *robust behaviour*[10] in dynamic, unpredictable environments.
- They do not require rich world models, and thus *can function in the presence of uncertainty and incomplete knowledge*, as is the case for our application.
- They do not need to simplify the search space, which often introduces unrealistic static world assumptions.

The main task for our coordination process is to avoid negative interactions between weapons and take advantage of the positive ones. In our case, for simplicity, the coordination consists only of identifying negative interactions between the Chaff and the Surface-to-Missile (SAM). Thus, the optimal positioning of the ownship to face a certain

[10]By robustness one means here that the planner will still show acceptable behaviour, although the operating conditions are different from the intended ones in some measurable ways.

number of threats is found in the coordination process. We remove from the SK plan the Chaff that will be deployed in the same direction as a SAM. To avoid obstructing the STIR view, the Chaff cannot be deployed within ± 0.2 radians of the direction of a SAM. Also, we look whether a SAM will be deployed in the same direction as existing Chaff. If we cannot delay the SAM launch by 3 seconds, we take it out the plan.

There are many ways to coordinate the two HK and SK agents. For instance, we can use a Central Coordinator (inspired from the centralized planning with distributed plans technique [6]), which, after receiving the two plans, one from each agent, will merge them. If there are negative interactions between the planned actions, it will modify the plans to eliminate those negative interactions, or if not possible, it will try to reduce their effects.

Another method [11], similar to Central Coordinator, is to assign the coordination task to one of the two agents. In the context of shipboard Combat Power Management (CPM), it is assumed that the HK agent has more constraints than the SK agent. Therefore, the coordination task can be assumed by the HK agent, which will however have to incorporate SK constraints during the elaboration of the global plan.

The last method is inspired by the Partial Global Plan (PGP) [12] discussed in Section 3.2. This method coordinates agents with the best abstract information possible. There are many levels of abstractions of the information and in each situation we must choose the right one to gainfully enhance collective performance. These different approaches are discussed in the following sections.

4.1 Hardkill/softkill coordination using central coordinator

The first considered coordination technique is based on the Central Coordinator concept. Figure 2 shows the different modules and the interactions between HK and SK agents while using a Central Coordinator agent for the specific naval CPM problem.

The coordination starts when both HK and SK agents have received the input data concerning the threats. Then, the two agents generate their respective plan (independently). These partial plans are sent to the ship CPM agent that acts as coordinator. As such, the ship CPM agent will be in charge of merging the two partial plans in a (SAM-Chaff) conflict free global plan. Coordination will also be performed with ship manoeuvring to find the optimal positioning (see Chapter 5) before sending the global plan to the plan execution agent.

4.2 Hardkill/softkill coordination using Hardkill Agent as a coordinator

This approach is similar the Central Coordinator one, with the difference that the Hardkill Agent performs the coordination task. The rationale of this choice lies in the fact that it is easier to incorporate a less constrained plan (*i.e.*, SK in the application of interest) into a more constrained plan (*i.e.*, HK) than the reverse. Another reason why the HK

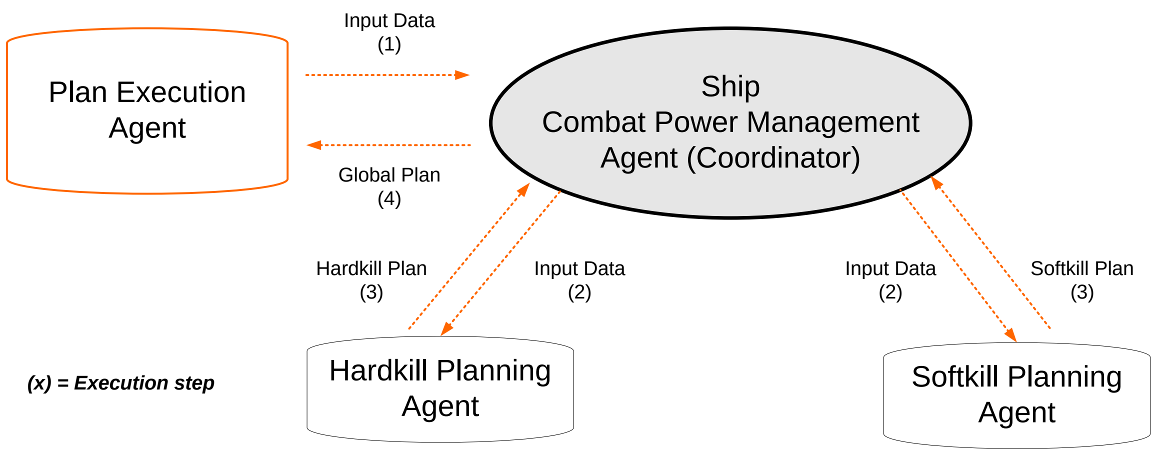


Figure 2: *Data flows in the Central Coordinator planning process*

planner was chosen to merge the two plans is because its plans take more time (due to the complexity) to be produced than the SK ones. When the HK planner is done, the SK plan is already available for coordination and no time is wasted in waiting for the other agent's plan. Figure 3 shows the different modules and interactions between the HK and SK planner when the Hardkill Agent is used as coordinator.

In this case, when the Softkill Agent has finished its planning, it sends the SK plan to the Hardkill Agent, which takes this plan and tries to integrate it into its own plan. When the "integration" is completed and the optimal positioning for the ownship is found, it sends the global plan to the plan execution agent.

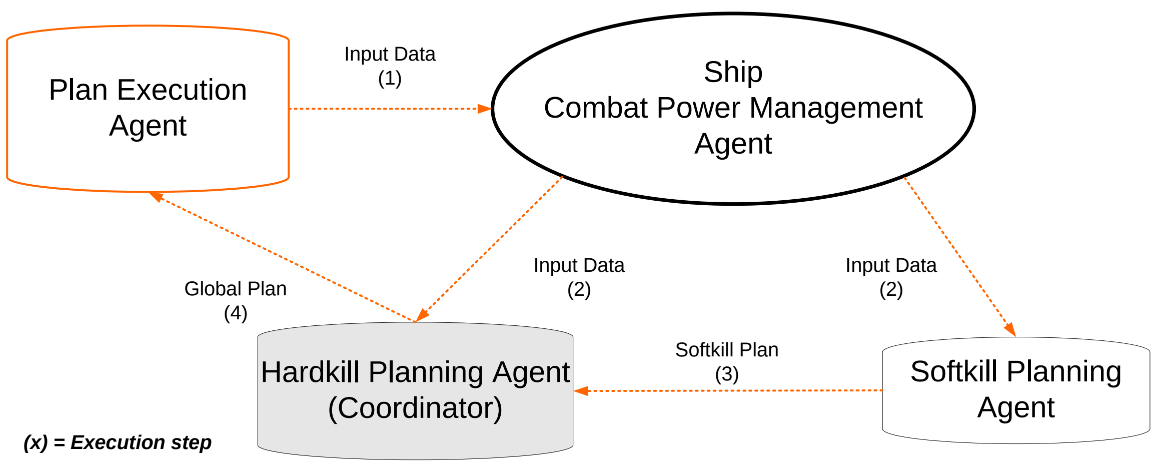


Figure 3: *Data flows in Hardkill Agent as a coordinator planning process*

4.3 Hardkill/softkill coordination using partial global planning

A simplified version of the Partial Global Planning (PGP) approach was used to satisfy the hard time constraints imposed by the application. The focus has been on the abstraction of

the information exchanged between the two planning agents. Thus, after the HK and SK agents have produced their initial plan, they evaluate which constraints the other agent has to satisfy. The constraints are then exchanged in the most compact mode possible to save time and memory space. Then, the two planning agents modify their respective plans to satisfy the other agent's constraints. After that, they send their individually coordinated plan to the ship CPM agent, which merges them. This agent assumes that these plans are valid as a complete plan, and then finds the optimal positioning of the ownship. Finally, the global plan is sent to the plan execution agent.

Figure 4 shows the different modules and the interactions between them according to the PGP method.

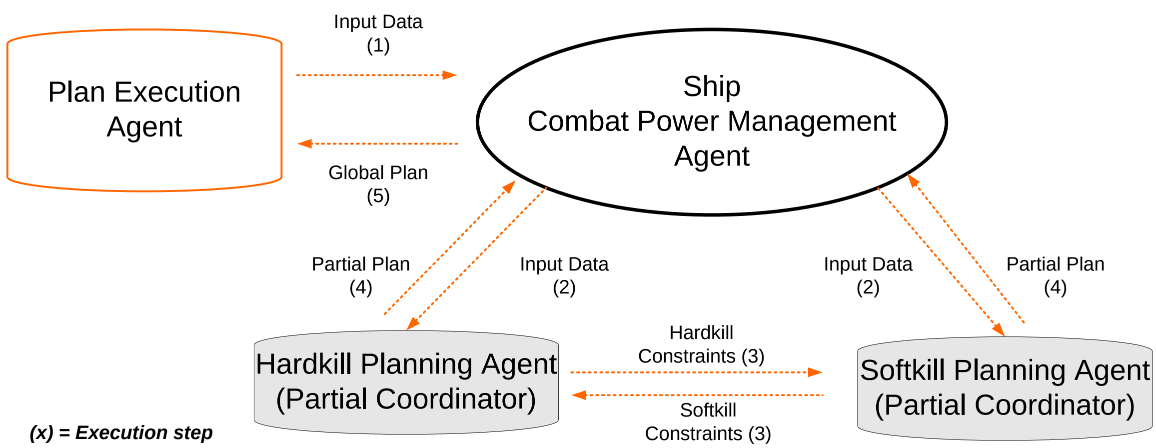


Figure 4: *Data flows in the Partial Global Planning process*

4.4 Comparison of coordination techniques

To evaluate and compare the above-presented coordination techniques, the developed simulator described in Annex B was used. The coordination techniques were tested using the Partly and Holistic Re-engagement planners described in [2] and defined here.

Partly Planner – uses very low-level reasoning techniques in order to elaborate a response to a situation in a very short reaction time. This is very important in CPM context because defending ownship brings a very hard and usually very short time constraint. For this planning mode, the HK agent maintains a list of threats moving toward the ownship. This list is sorted (from the most to the least dangerous threat) according to some form of threat evaluation. For this implementation, threat evaluation considers only the Closest Point of Approach (CPA) of the threat to the ownship, and the estimated time for the threat to reach CPA. Then, the HK agent applies some predefined rules for allocating the resources.

Holistic Re-engagement Planner – While the Partly Planner plans only for the two most threatening targets, Holistic Re-engagement planner considers all the targets. It works as follows: a decision tree is first produced that explicitly considers, in a

probabilistic manner, all possible outcomes of a particular action. In fact, such a tree reflects a plan with different conditional branches. That allows taking into account results of actions. For instance, during the plan execution, one should follow one branch or another depending on the result of an engagement to some threat $\mathcal{T}(i)$. If this engagement has succeeded, then the plan continues by following a branch where it does not consider the threat $\mathcal{T}(i)$ anymore. If the engagement has failed, then a branch where other engagements are planned for $\mathcal{T}(i)$ is executed. All these conditional branches reflect contingent plans that are very important since the outcomes of the engagements are uncertain. Note that without conditional branches, the time horizon of the plan would be very limited and it would be needed to re-plan each time an engagement fails. The latter can take a long time, thus causing problems for the subsequent engagements.

The scenario considers a varying number of similar (subsonic) threats with $CPA = 0$. This section presents and discusses general results. More specific discussion are given in the next two subsections. Table 1 and Figure 5 summarize the average time (in seconds) it took to plan and coordinate the 300 tests for two defence modes (Partly and Holistic Re-engagement) using the three coordination techniques: the Central Coordinator, the Hardkill Agent as a coordinator, and the Partial Global Planning (PGP).

Note that each attribute of interest was tested over 20 runs with a number of threat(s) varying from 1 to 15. In total 300 (20 $\times$ 15) tests per attribute were performed. The results are presented with their confidence interval ($x \pm y$) at 95%.

	Partly	**Holistic Re-engagement**
Central coordinator	$2.44sec$	$3.09sec$
Hardkill agent as a coordinator	$3.61sec$	$3.74sec$
PGP	$3.66sec$	$4.55sec$

Table 1: *Average coordination time for two defence modes versus three coordination techniques*

It can be noticed that, when considering coordination as well as planning perspectives, the Partly and Holistic Re-engagement modes both take less time using the Central Coordinator technique. The PGP technique is the slowest one, because there are more communications in this technique than in the two others. In such real-time applications, communications should be avoided as much as possible, because they are very time consuming.

Figure 6 (a) gives, for different numbers of threats, the results for the planning times under the Partly mode for the three considered coordination methods. It can be seen that the Central Coordinator method is better than the two other methods for all the numbers of threats.

Similarly, Figure 6 (b) gives the results for the planning times under the Holistic Re-engagement mode. Here also, it can be seen that the Central Coordinator method is better than the other methods for all the numbers of threats. This can be explained by the

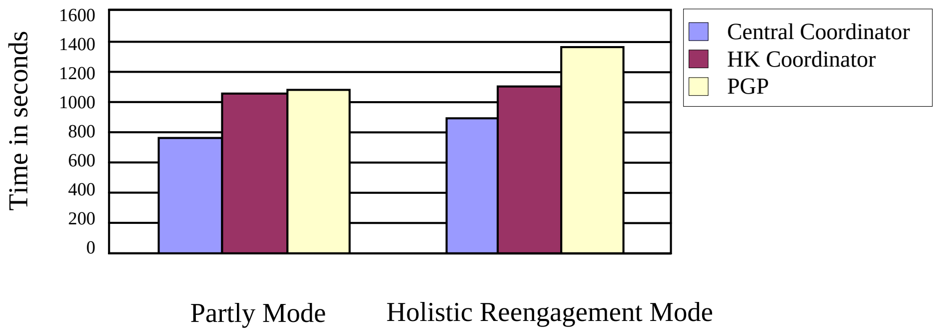


Figure 5: *Planning time under two defence modes*

high number of iterations that may require the Hardkill Agent and the PGP coordination approaches to obtain a conflict global plan. No iteration is required in the case of the approach that uses a Central Coordinator.

In the next subsection, the two used defence planning modes (Partly and Holistic Re-engagement) will be tested using the Central Coordinator technique.

4.4.1 Central coordinator results

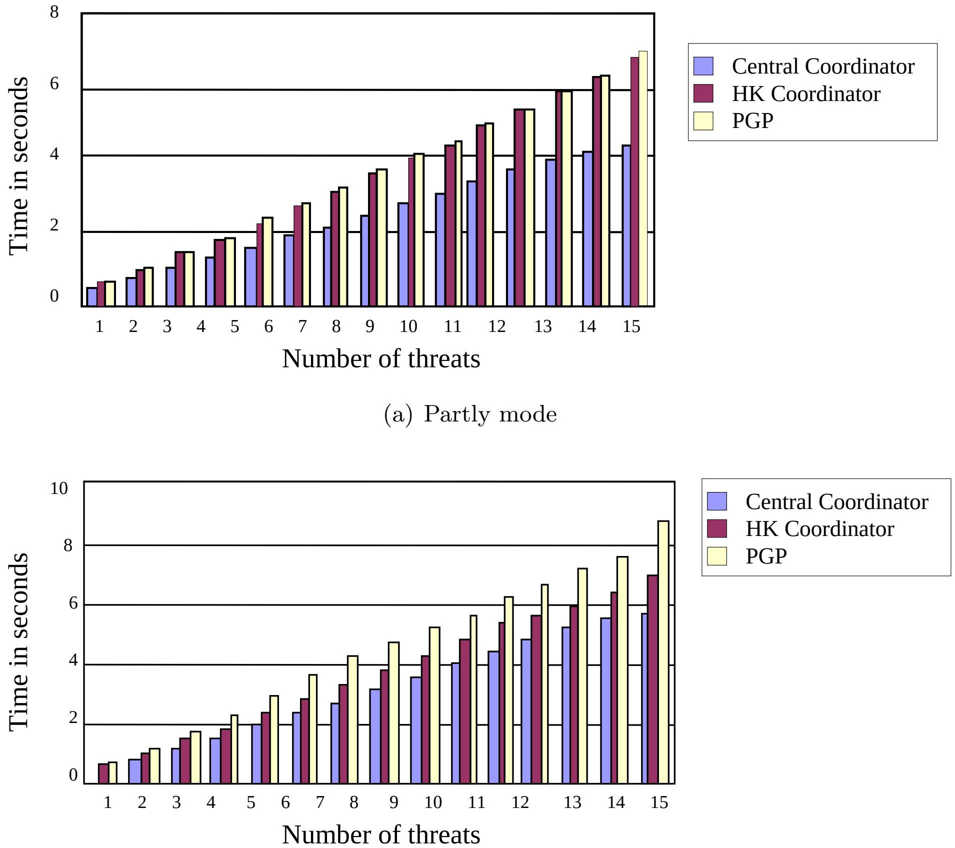
To coordinate the HK and the SK planners, the Central Coordinator technique (§4.1) is used. Notice that survival (*i.e.*, no hit) here is considered without positioning.

A possible explanation of the results on coordination is that the Chaff may be in conflict with the HK weapons. This becomes more prevalent as the number of threats or the number of Chaff clouds increases. This can be explained by the fact that the Chaff clouds are relatively large and they remain in the air a long time before being dissipated, and may block threat(s) from the STIRs used to direct HK weapons. Furthermore, unlike the actual Halifax Class Frigate, these tests do not yet consider navigational manoeuvres of the ship to reduce these conflicts [11]. Consequently, in our model, and due to the fact that the HK weapons are privileged, the Chaff is often not deployed.

Figure 7 shows the results for the Central Coordinator with respect to the two different planning modes. Overall ship survival probability (without positioning) is 87.9% $\pm$ 1.3 for Partly Planner and 90.9% $\pm$ 1.2 for Holistic Re-engagement Planner for both HK and SK weapon systems.

Partly and Holistic Re-engagement algorithms show similar global efficiency. The Holistic Re-engagement mode presents results that are slightly better (3.0%) than those presented by the Partly mode. However, we can see that they do not have the same effectiveness when the number of threats attacking the ownship changes. The Holistic Re-engagement mode is

[11] Ship manoeuvres will be considered in Chapter 5



(a) Partly mode

(b) Holistic Re-engagement mode

Figure 6: *Planning time according to the coordination under two defence modes*

better than the Partly one when there are only a few threats attacking the ownship. This is caused by the fact that the Holistic Re-engagement mode uses re-engagements of SAMs to face threats. When there are few threats, it is easier in terms of resource management to deploy another SAM to a threat when the first one fails. However, when there are several threats attacking the ownship, the advantage for the Holistic Re-engagement planner is lost because the resources are used at their full capacity for both modes almost all the time [2]. Nevertheless, the results come to be quite equal as the number of threats approaches 15.

Figure 8 compares results of the Partly mode, where SAM is fired at the latest or earliest time possible. The overall ship survival probability (without positioning) is 87.9% $\pm$ 1.3 for the earliest firing time and 83.5% $\pm$ 1.5 for the latest.

One can note that firing SAMs at the latest time possible is more efficient (by 4.4%) than firing SAMs at the earliest time. Firing in the earliest mode is usually made just after the radar of the ownship perceives the threat. The difference of effectiveness between the two methods is due to a better resource management, because the STIR is less used when we

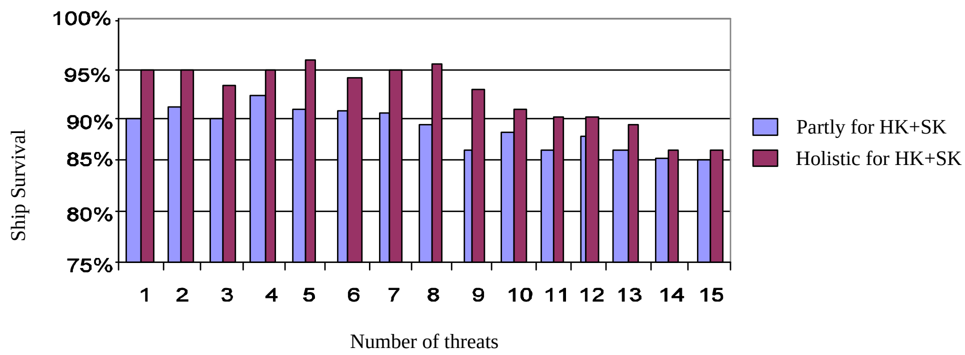


Figure 7: *Results of the Partly and Holistic Re-engagement planning modes*

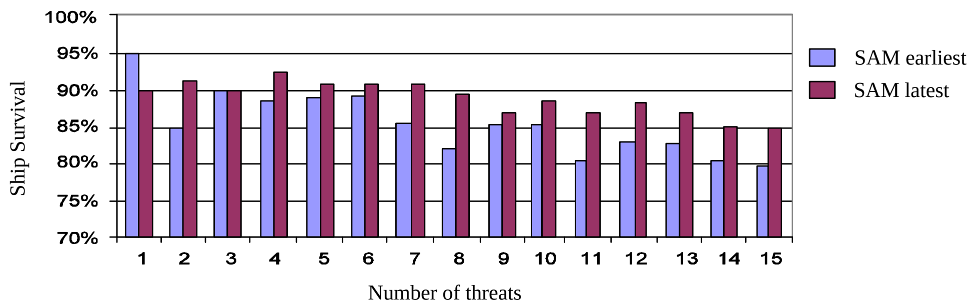


Figure 8: *Partly planning by firing SAMs at the earliest or latest time possible*

fire at the latest time possible. We can use only two STIRs to control SAMs, so we must use them very carefully, and they must not guide a SAM during a too long period because in the mean-time they cannot do anything else. Firing SAMs at the latest time possible help optimize the management of the resources.

Figures 9 and 10 compare the Partly and Holistic Re-engagement when we use the SK weapons only, HK weapons only, or when we coordinate both types of weapons to face diverse attack scenarios.

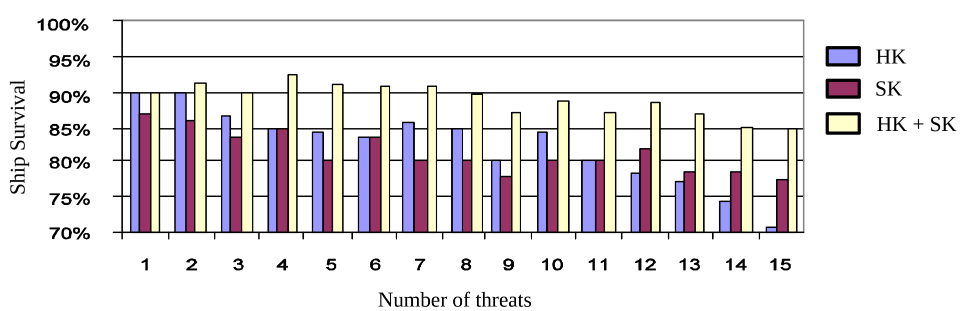


Figure 9: *Partly planning system using Hardkill, Softkill or both strategies*

Table 2 summarizes the ship survival rate using the HK, softkill, or the coordinated use of both weapons. We can make some remarks from these results:

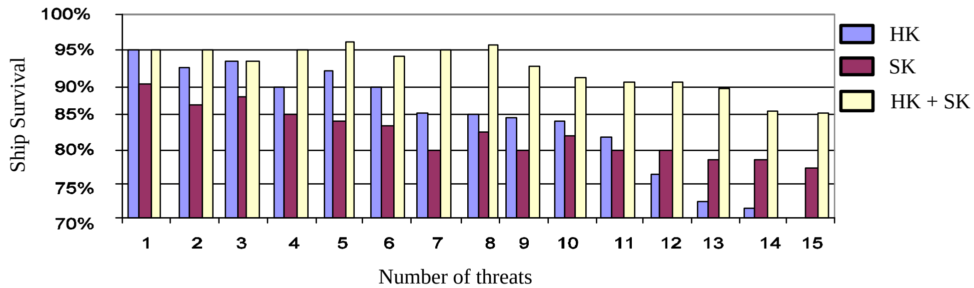


Figure 10: *Holistic Re-engagement planning using HK, softkill or both*

1. **The global efficiency of the HK and SK weapons is almost similar. The HK mode is better with few threats but less effective with multiple of threats than the SK mode**. For the HK weapons, we generally assume the effectiveness to destroy a threat for a SAM is 75%, and for the CIWS is 0.6% per round. Notice that the Gun is used very rarely. When one is in face of few threats, the ownship has more chance of survival because it can use the CIWS against a larger number of threats. When the CIWS is used against two or three threats, there are no more units available to face another threat, which is less effective with a scenario with several threats; as there are only two STIRs available, difficulties arise when facing more than two threats simultaneously.

   When SK weapons are used alone, the Chaff is used more than when combined with HK. In this situation, one generally can assign a Chaff and a Jamming to each threat, resulting in an 80% survival chance for the ownship. There are 30 units of Chaff, which can be used with almost no restriction. The Jamming has some usability constraints. There are two Jamming antennas that can each engage two threats, which provide four engagement channels. Based on the above, one can see that SK weapons offer more flexibility than the HK weapons.

   In general, the scenarios show similar results, because when the HK weapons can be used without resource constraints, they are more effective than the SK weapons. This occurs with scenarios having few threats. On the other hand, SK weapons are more effective to face more threats.

2. **Using both the SK and HK weapons improves the survival chances of the ownship**. One can obviously see that there is a synergy effect in the coordinated use of the two types of weapons. In general, one uses the original HK plan along with the Jamming in the global planning, which is better than using the HK or the SK only.

3. **Results of the Holistic Re-engagement mode are slightly better than the Partly mode**. Although this difference is small, it must be should considered, because the two algorithms are similar aside from the fact that the Holistic Re-engagement mode generates a plan for all visible threats.

4. **Hardkill results for the Holistic Re-engagement mode degrade faster than the Partly mode**. As it has been explained previously, the HK Holistic Re-engagement

planning system is more effective against a few threats but it leads to resource management (STIR) problems more rapidly than the Partly planning. It is the reason why it becomes less effective to face an increasing number of threats.

	Partly	**Holistic**
Overall survival with SK only	$79.7\% \pm 1.6$	$80.3\% \pm 1.6$
Overall survival with HK only	$79.7\% \pm 1.6$	$80.2\% \pm 1.6$
Overall survival with the coordination of both	$87.9\% \pm 1.3$	$90.9\% \pm 1.2$

Table 2: *Results of using HK, SK or both weapon systems*

It was noticed that the Holistic Re-engagement planner is clearly better than the Partly planner when few threats attack the ownship, but the two planners offer similar results when many threats attack. So it could be interesting to have a meta-level agent that decides which kind of planner to use according to the situation. This could be implemented using a meta-deliberation technique. Such a meta-deliberative agent could also be useful to decide which kind of coordination technique can be used to merge the HK plan with the SK plan. However, it was noticed that the Central Coordinator technique was clearly the more efficient with the Partly and Holistic Re-engagement planner.

5 Engagement and ship position coordination

The positioning and the manoeuvring of the ownship may play a key role in the ship's defensive plan. The ship navigation needs to be coordinated with the weapon deployment in order to increase the ship's survivability and effectiveness during engagements. Different constraints exist that may require the ownship to be suitably positioned. The following give examples of types of constraints.

1. **Blind Zones** – some weapons cannot view particular threats and are therefore unable to shoot when the ownship is not well oriented with respect to the threat bearing during the construction and the execution of a defence plan. The appropriate orientation of the ship can improve the effectiveness of the different strategies by clearing required blind zones (Figure 11).

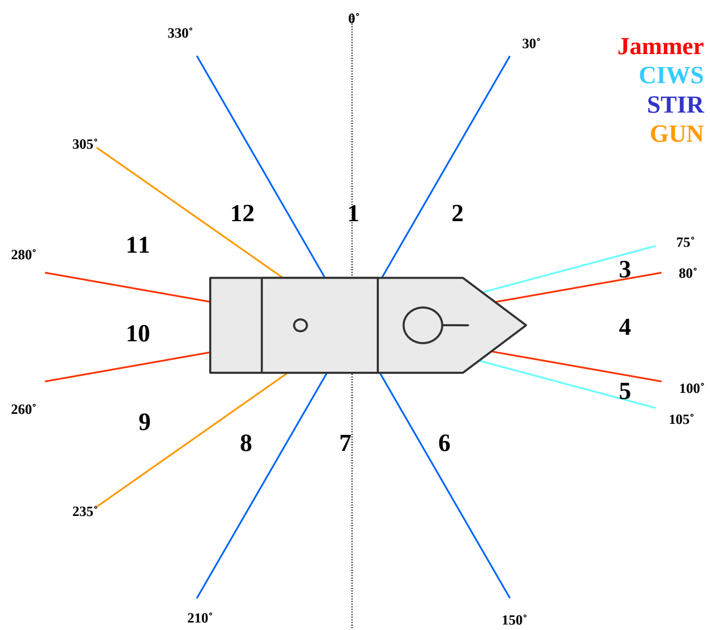


Figure 11: *Resource Blind Zones*

2. **Signature Reduction** – this constraint imposes to the ownship a movement that reduces the Radar Cross-Section (RCS) exposed to incoming threats, since the capability of threats to lock onto the ship is directly related to the ship geometry (Figure 12) and the orientation (Figure 13).

   A combination of the geometry and the orientation defines the ship RCS seen by the threats. Thus, the selection of appropriate ship positions and orientation helps make it considerably harder for threats to lock and keep a lock on the ship.

3. **Damage Reduction** – this concerns constraints and requirements for the ship positions in case of potential hits in order to minimize the damage of ship's vital resources.

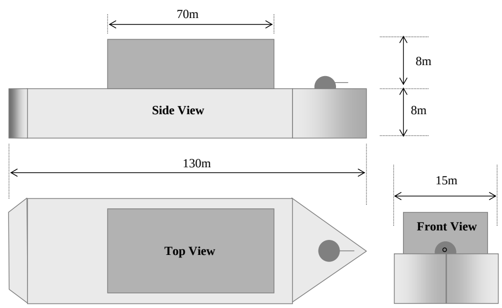


Figure 12: *Ship geometry*

4. **No fire zones** – this concerns constraints imposed by the presence of other non-hostile platforms,*e.g.*, protected High Value Unit (HVU), friendly ships, neutral vessels, etc. (Figure 14).

These types of constraints will not be all addressed by the current work, and focus will be put only on blind zone coordination.

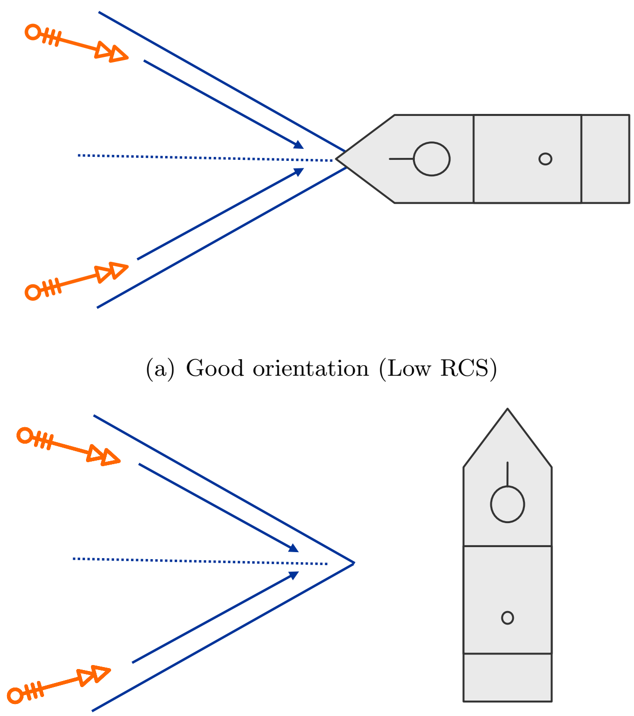
5.1 Blind zone-based coordination

Since the effectiveness of a particular weapon varies depending on the orientation of the ownship with respect to the threats faced, a key element of the coordination process is to manoeuvre the ownship to most effectively use all the weapons available, that is to reduce the constraints due to the weapon blind zones. To find the most appropriate orientation of the ownship, the surrounding environment is divided into several sectors based on the HK and SK engagement availability and capability, as shown in Figure 11. These sectors will have to move along with the ownship, and maintain the same relative orientation to the ownship.

5.1.1 Dependence on ship positioning

First of all, it is very important to look at the elements of the ownship for which efficiency depends on the ownship positioning. As the defence of the ship depends mostly on HK and SK efficiency, the focus will be here on these weapons elements because their efficiency depends on the position and orientation of the ship. Figure 11 shows the various angles that give the different engagement capabilities of the HK and SK weapons, as described below.

1. **SAM** — It has no blind zone for launching missiles. The two STIRs can each guide a SAM to different targets from 0° to 30°, from 150° to 210° and from 330° to 360°, if it is assumed that 0° is to the left of the ship (see Figure 11). In the other situations, only one STIR is available to control the missiles.



(a) Good orientation (Low RCS)

(b) Bad orientation (High RCS)

Figure 13: *Radar Cross-Section based on ship orientation*

2. **GUN** — It has a blind zone of ±35° from the back of the ship. Otherwise, the targeting ability of the Gun with a STIR follows the same rules as the SAM.

3. **CIWS** — It has a blind zone of ±15° while looking to the front of the ship. Otherwise, targets can be engaged (one at a time).

4. **JAMMING** — One can use either of two antennas for Jamming at ±10° to the front and the rear of the ship. Otherwise, only one antenna can be used.

5. **CHAFF** — Chaff can be used in any direction when needed, and so will not directly influence the orientation of the ship.

5.1.2 Effectiveness sectors

To find the optimal positioning of the ship, the environment can be divided into twelve zones. The latter surround the ship and are defined based on the HK and SK engagement possibilities shown in Figure 11. Table 3 describes these twelve distinct zones, showing the angular coverage of a zone and the difference in the weapon engagement capabilities of a zone compared to the Normal state. The Normal state at any one time has one STIR available for a SAM and a Gun engagement, the CIWS able to engage threats, one possible Jamming engagement, and Chaff available.

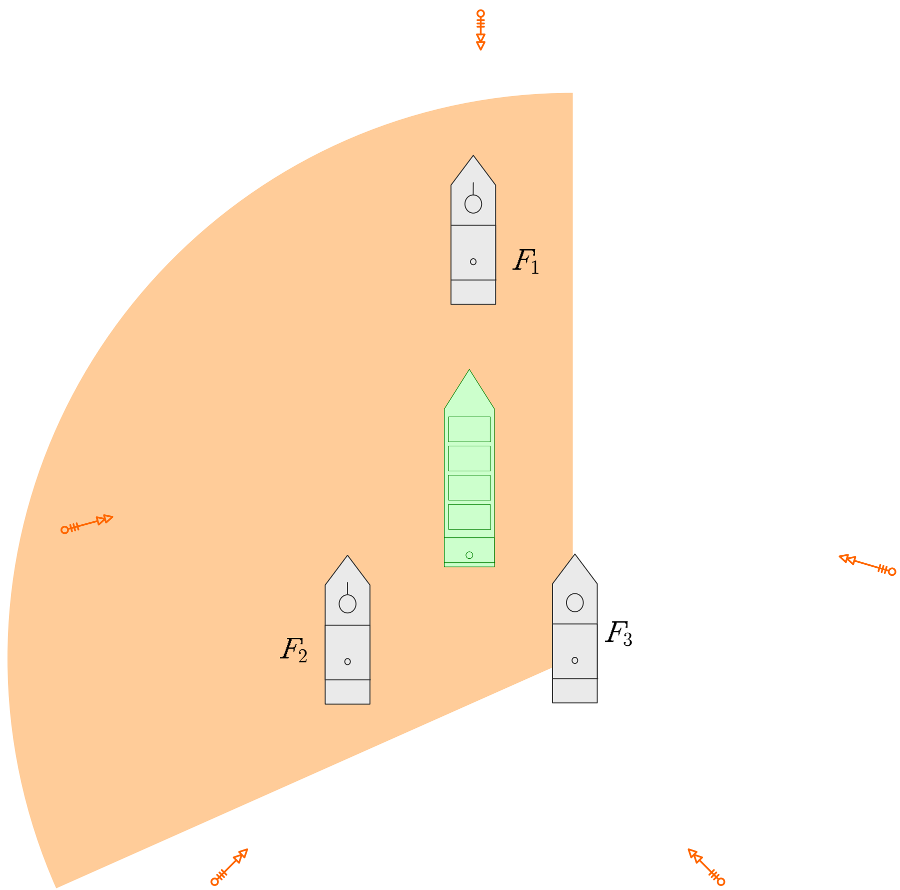


Figure 14: *Example of No-fire zone*

All the zones in Table 3 that have the same state (as indicated in the “Difference from Normal State” column), can be amalgamated to form a new representation of the engagement capability sectors:

Sector A = Zone 1 + Zone 7

Sector B = Zone 2 + Zone 6 + Zone 8 + Zone 12

Sector C = Zone 3 + Zone 5

Sector D = Zone 4

Sector E = Zone 9 + Zone 11

Sector F = Zone 10

This establishes six distinct sectors, for which a series of tests were conducted to determine their respective effectiveness. The effectiveness of each sector was determined using varying numbers of threats at short, intermediate, and long ranges, under various planning modes

Zone	Angles Covered	Difference from Normal State
1	330° — 30°	One additional STIR
2	30° — 75°	No difference
3	75° — 80°	No CIWS
4	80° — 100°	No CIWS, but one additional Jamming engagement possible
5	100° — 105°	No CIWS
6	105° — 150°	No difference
7	150° — 210°	One additional STIR
8	210° — 235°	No difference
9	235° — 260°	No Gun
10	260° — 280°	No Gun, but one additional Jamming engagement possible
11	280° — 305°	No Gun
12	305°— 330°	No difference

Table 3: *Description of the effective sectors for engagements with HK and SK weapon systems*

of defence. The effectiveness was specified as the probability to kill a threat in a sector. With these measures of effectiveness for the various sectors, it was possible to estimate the optimal position and orientation of the ship using a Bayesian approach (see S 5.1.4).

5.1.3 Movement of the ship

It is important to understand the ship's movement capabilities in order to build plans that incorporate such movements. Obviously, these plans must be realistic so that the ship can execute them. The knowledge of the possible movements will largely help the development of these plans.

As a guideline, assume that it takes at least a minute to turn the ship by 180°. It is extremely probable that such a manoeuvre will not be necessary because the various zones are symmetrical. On the other hand, the ship does not merely rotate on a point when it turns. It is assumed that it turns by moving through an arc with a turning radius of 270 m, when it does turn 180°. It is consequently possible to use fractions of these numbers when displacements are smaller.

5.1.4 Method for orienting the ship

It is very important to select the most appropriate position for the ship. Nevertheless, in certain situations, the ship positioning may reduce the effectiveness of the defensive plan. As an example, an engagement plan, which is being executed, could be suddenly interrupted by the ship movement. If a SAM is already in the air during the construction plan that suggests moving the ship into a new position, the movement may put the launched SAM into the STIR blind zone before the kill assessment can be carried out.

The general algorithm of positioning of the ship is presented. Then, the Bayesian approach

that will be used to determine the optimal position of the ownship is explained in detail.

There are four regions of effectiveness for the ship:

1. A region where both HK and SK are effective.
2. A region where only the HK is effective.
3. A region where only the SK is effective.
4. A region where neither the HK or the SK is effective.

In these conditions, the defence system will try to have the maximum number of targets in the "both effective" area, and as few as possible in the "neither-effective" area. Although it increases the chance of weapon interaction, it is in the "both effective" area that the ship will have the greatest probability of survival.

A method that considers these facts is proposed, without trying to directly put the maximum number of threats in the "both effective" area and the minimum in the "neither effective" area. We use a more effective method that maximizes the average probability of killing all threats. This is done by turning the ship in the "best" position and orientation.

To determine ship manoeuvres, we use a learning module. A fundamental issue is how to assure that the chosen positioning is the best one. Firstly at the time of learning, we will have to find a method, which supposes that the ship turns at an infinite speed. It will be necessary to make this assumption to avoid falling into local optima, in other words, to not be able to go to the right position because of the speed constraint of the ship. It is very probable that the ship will not have time to effectuate a 180° turn to modify its position to defend itself but if the ship had been elsewhere (*i.e.*, 10° from the best place), it would have been likely more able to make the move.

We tested two defence modes on the ship: the Partly and Holistic Re-engagement planning modes. Our strategy is to test the efficiency of each of the six engagement capability sectors with 20 different scenarios from 1 to 15 missiles, thus making 300 tests per defence mode per sector. We will have to repeat this procedure 30 times for each defence modes because we have 6 distinct sectors and 5 ranges of numbers of threats (1 to 3, 4 to 6, 7 to 9, 10 to 12, and 13 to 15). The results will be presented in Section 5.2. Algorithm 3 gives a general overview to find the optimal position of the ship.

The remaining part of the current section explains the last point of this algorithm and provides a complete example of the method. It will particularly explain how the position of the ship is computed using a Bayesian approach [13].

5.1.4.1 Bayes theorem

Before defining the Bayesian theorem, one introduces the following notations:

Algorithm 3 Ship positioning

Function BAYES-POSITIONING(*threats-list*) **return** a plan
while preparing the HK plan **do**
  if we cannot use a weapon because of the positioning of the ship **then**
    if we have the time to move to use the weapon **then**
      Memorize the engagement
    else
      Do nothing
    end if
  end if
end while
send to the mediator the HK plan and all the memorize engagements that could be executed if we move the ship
while preparing the SK plan **do**
  if we cannot use a weapon because of the positioning of the ship **then**
    if we have the time to move to use the weapon **then**
      Memorize the engagement
    else
      Do nothing
    end if
  end if
end while
send to the mediator the SK plan and all the memorized engagements that could be executed if we move the ship
Once all plans from HK and SK agents have been received and merged, the mediator tries various positioning combinations according to a Bayesian method
return the plan and the positioning for the ship to the execution agent

1. $P(h)$ is the initial probability that hypothesis h is true, before having observed the training data. If we have no initial knowledge, we can assign the same $P(h)$ for all the assumptions.

2. $P(D)$ is the probability that a given training data D is observed.

3. $P(D|h)$ is the probability of observing a data D when hypothesis h is true.

4. $P(h|D)$ is the probability that h is true according to observed training data. In our case, it is this probability that interests us more.

Bayesian theorem states:

$$P(h|D) = \frac{P(D|h) \times P(h)}{P(D)} \tag{2}$$

In several cases, we want to know the assumption that has the highest probability $P(h|D)$ after having observed the data. This is called the MAP (maximum *a posteriori*) hypothesis.

$$h_{MAP} = \arg\max_{h \in H} \Big[P(h|D) \Big] \tag{3}$$

$$= \arg\max_{h \in H} \Big[P(D|h) \times P(h)/P(D) \Big] \tag{4}$$

$$= \arg\max_{h \in H} \Big[P(D|h) \times P(h) \Big] \tag{5}$$

In the last step (Equation 5), we removed $P(D)$ because it is a constant independent of h.

5.1.4.2 Naïve Bayes classifier

The method of naïve Bayes classification is used to find the optimal position of the ship. This method is known as naïve because it is based on the simplifying assumption that the attribute values are conditionally independent given the target value. Whenever this assumption is satisfied, the naïve Bayesian classification is similar to the MAP classification. Therefore we obtain the hypothesis, which has the strongest chance of being true, *a posteriori*. Mathematically, this assumption is translated by supposing that the probability of observing the conjunction $a_1, a_2, \dots a_n$ is only the product of any individual attribute probabilities:

$$P(a_1, a_2, \dots a_n|v_j) = \prod_i P(a_i|v_j) \tag{6}$$

where a is an attribute and v its value. The problem is to find a value that maximizes the *a posteriori* probability. Naïve Bayes classifier gives

$$v_{NB} = \arg\max_{v_j \in V} P(v_j) \prod_i P(a_i|v_j) \tag{7}$$

In Equation 7, v_{NB} denotes the target value output by the naïve Bayesian classifier. In this method, the number of distinct $P(a_i|v_j)$ terms that must be estimated from the training data is just the number of distinct attribute values multiplied by the number of distinct target values. So V is the finite set of values that an attribute a can take. This method can apply very well to determine the optimal position that the ship must have when is attacked by one or more Anti-Ship Missiles (ASM). What the various terms of the method means for our problem is:

1. V is the group of possible positions that the ship can take as proposed by the algorithms HK and SK (possible solutions).
2. $P(v_j)$ is the number of times that a position was retained compared to the set of the possible positions. At the time of learning, the threats come at a random direction

toward the ship. So the probability that a threat comes from a certain angle is the same from another angle. Thus, we can consider this term as a constant and by this fact, we could ignore it.

3. $P(a_i|v_j)$ represents the probability of defending itself from a certain threat when the ship is at a certain position/orientation. $P(ASM\#2|15°) = 0.85$ means that the ship has 85% of chance to survive missile #2 when it is at the 15° position. The percentage of the survival chances is given by learning module.

So for this method to give a MAP hypothesis, it is necessary that different attribute values for a_i, which corresponds to the designation of an ASM, are conditionally independent, given the target value (v_j), which is a new positioning for the ship. Therefore, it is necessary that the various angles of ASMs are independent of the position/orientation of the ship *a priori*.

The following two sub-sections present exemplar scenarios of how the effectiveness of the defined sectors influence the engagement plans.

5.1.5 Scenario 1

The scenario considers two threats coming toward the ship as represented in Figure 15. The ship is positioned at 90° (toward the east), which puts the two threats in Zone 6 of the sector's representation; there is no difference from Normal state. Let us suppose also that these two threats attack the ship at almost the same time, so the ship resources will have to be assigned separately within these two threats. The two ASM threats attack the ship with an angle of 140° for threat #1 and 135° for threat #2.

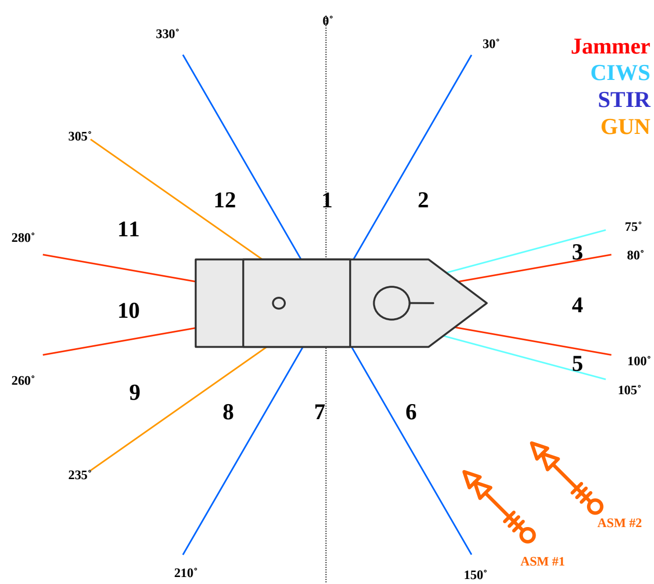


Figure 15: *Example of a defence situation*

Let us suppose we are in the Holistic Re-engagement mode. First, the HK and SK plans could be made as follows.

Hardkill plan

1. Throw 1 SAM against threat #1, with the possibility to re-engage threat #1 with the front STIR (STIR A) if the first SAM misses it.

2. Throw 1 SAM against threat #2 with the front STIR (STIR A) if threat #1 is destroyed by the first SAM thrown at it.

3. Use the CIWS against threat #1 and threat #2.

   If we cannot use a weapon because of the positioning of the ship and if we have the time to move to use the weapon, then memorize the engagement

4. Throw 1 SAM against threat #2 and having the possibility to re-engage threat #2 with the rear STIR (STIR B) if the first SAM misses.

   In this situation, we would propose one new position for the ship. To find the proposed position(s), we find the nearest sector surrounding the ship that enables the use of a supplementary resource and add 1.5° just to be sure that the threat is inside the right sector. Here, by putting threat #2 into Zone 7, we would be able to shoot a SAM against it because in Zone 7 we can use the rear STIR.

   The proposed position will be of 73.5° by turning the ship left (16.5° turn).

Softkill plan

1. Use the Jamming against threat #1 and threat #2.

2. Use the Chaff against threat #1 and threat #2.

   If we cannot use a weapon because of the positioning of the ship and if we have the time to move to use the weapon, then memorize the engagement.

   Here, we have no engagement that we cannot make, because the resources can be used without any limitation. The coordination process would cancel the two Chaff deployments in the global plan because they could interfere with a SAM that we could shoot.

After that, we would have to find the ship positioning by making two naïve Bayesian calculations. The first one is to calculate the actual position because we want to find the most effective sector. Then, we will calculate the efficiency of moving the ship to the 73.5° sector. We have to refer to Table 6 to obtain the efficiency of the different sectors while engaging in the Holistic Re-engagement mode for the following calculation.

1. Current positioning (90°, in Zone 6): $0.958 \times 0.958 = 0.918$

2. Proposed positioning (in Zone 7): $1.0 \times 1.0 = 1.0$

Thus, the highest overall survival probability is 1.0, *i.e.*, the ship orientation angle of 73.5° is "ideal" for the ship to face these threats. So in this situation, the ASMs that had angles of 135° and 140° would now have angles of 151.5° and 156.5°. So both ASMs would now be in Zone 7 of the ship instead of Zone 6, which is more efficient. Thus, we would be able to shoot two SAMs against both threats instead of only using one SAM against threat #1.

5.1.6 Scenario 2

Consider a scenario with 5 threats. Suppose the HK and SK planners individually suggest changes in ship orientation by 30°, 105°, 210°, 235°, and 330°, each would be allowing additional engagement capabilities. Furthermore, suppose the probability ($P(a_i|v_i)$) of ship survival for a threat engaged in the sector relevant to a given orientation is known, and specified in each cell of Table 4. Thus, the highest overall survival probability is 0.64, *i.e.*, the ship orientation angle of 235° is "ideal" for the ship to face these threats.

	Proposed Positions				
Threat	**30°**	**105°**	**210°**	**235°**	**330°**
# 1	.90	.88	.90	.85	.88
# 2	.95	.91	.78	.89	.90
# 3	.88	.89	.75	.92	.96
# 4	.77	.83	.86	.97	.98
# 5	.90	.92	.98	.95	.79
Product Probability	.52	.62	.44	**.64**	.59

Table 4: *Survival probability for each threat with different ship orientation angles*

5.2 Test and evaluation

To test and evaluate the proposed ship positioning approach, the Naval Defence Simulator (see Appendix B) environment is used. The Central Coordinator technique (see Section 4.1) approach is used to coordinate the HK and the SK planners. The tests were performed using both the Partly and the Holistic Re-engagement modes.

Each attributes were tested 20 times for all number(s) of threat(s) varying from 1 to 15, that 300 tests per attribute were run. The results break up into two parts. Firstly, we have the results of the evaluation of the different zones after the learning was made. Then, it is possible to re-evaluate the two different defence algorithms by using the positioning of the ship.

5.2.1 Learning module

Tables 5 and 6 summarize the learning (survival probability) made for the different sectors for the Partly and Holistic Re-engagement modes.

Threat(s)	Sector A	B	C	D	E	F
1 to 3	90.8 ± 5.2	90.8 ± 5.2	90.8 ± 5.2	85.2 ± 6.2	95.0 ± 3.4	89.9 ± 5.3
4 to 6	89.3 ± 3.5	91.0 ± 3.2	85.3 ± 4.0	86.0 ± 3.9	88.0 ± 3.7	86.3 ± 3.9
7 to 9	89.7 ± 2.7	88.0 ± 2.9	80.3 ± 3.5	84.5 ± 3.2	88.3 ± 2.9	86.5 ± 3.1
10 to 12	89.9 ± 2.3	85.3 ± 2.7	79.9 ± 3.1	82.7 ± 2.9	84.4 ± 2.8	86.5 ± 2.6
13 to 15	89.2 ± 2.1	81.8 ± 2.6	79.7 ± 2.7	79.2 ± 2.7	88.6 ± 2.0	85.7 ± 2.4
Overall	89.3 ± 1.2	85.6 ± 1.4	81.3 ± 1.6	82.4 ± 1.6	84.1 ± 1.5	86.3 ± 1.4

Table 5: *Learning results based on Partly planning mode*

Threat(s)	Sector A	B	C	D	E	F
1 to 3	100 ± 0.0	95.8 ± 3.6	94.2 ± 4.2	94.2 ± 4.2	97.5 ± 2.5	95.8 ± 3.6
4 to 6	96.7 ± 2.0	94.0 ± 2.7	92.0 ± 3.1	91.0 ± 3.5	91.0 ± 3.2	92.7 ± 2.9
7 to 9	95.6 ± 1.8	91.9 ± 2.4	80.4 ± 3.6	92.7 ± 2.8	89.0 ± 2.8	90.0 ± 2.7
10 to 12	92.4 ± 2.0	87.7 ± 2.5	80.2 ± 3.0	85.6 ± 2.7	88.0 ± 2.5	87.6 ± 2.5
13 to 15	91.3 ± 1.9	83.2 ± 2.5	80.5 ± 2.7	84.0 ± 2.5	85.5 ± 2.4	86.9 ± 2.3
Overall	93.6 ± 1.0	88.2 ± 1.3	82.5 ± 1.5	86.5 ± 1.4	88.2 ± 1.3	88.9 ± 1.3

Table 6: *Learning results based on Holistic Re-engagement planning mode*

5.2.2 Simulation results for ship positioning

Figures 16 and 17 compare the results with and without the positioning of the ship under both the Partly and Holistic Re-engagement engagement planning modes.

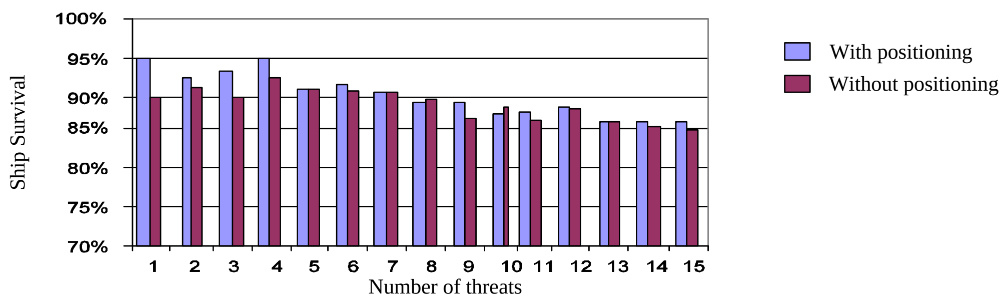


Figure 16: *Results with and without ship positioning under Partly mode*

Table 7 and Figure 18 show the total number of times the ship was hit, using the two planning modes, both with and without positioning.

5.3 Discussion

The following discusses the main factors that may explain the difference in the performance of the two planning modes.

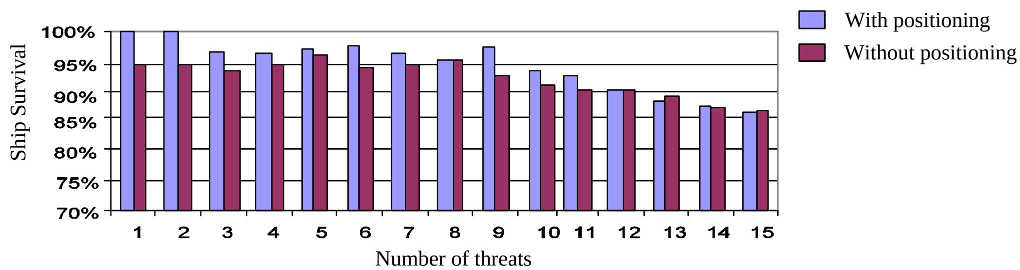


Figure 17: *Results with and without ship positioning under Holistic Re-engagement mode*

	Partly	Holistic Reengagement
General efficiency without positioning	87.9% ± 1.3	90.9% ± 1.2
General efficiency with positioning	88.7% ± 1.3	92.1% ± 1.1
Improvement	**0.8**%	**1.2**%

Table 7: *Results with and without ship positioning using both Partly and Holistic Re-engagement planning modes*

1. **A consideration of all visible threats during the planning** – Under the Partly mode, we do not modify an existing plan to counter a threat when a new threat is detected. We generally have one threat response per plan. The Holistic Re-engagement mode offers a plan for all visible threats. It is important to have a view of all incoming threats to choose the optimal position of the ship. Under the Partly mode, the ship will have a good position to face a fraction of the threats, which is less effective.

2. **The standard deviation of section effectiveness** – The greater the standard deviation between the different sectors for a mode is, the greater the percentage of improvement of using the positioning of the ship will be for a particular mode. For example, the worse case would be when the 6 sectors have the same efficiency, so then re-positioning the ship would give little improvement. But if there are sectors that are better than others, the ship will orient itself to face the majority of the incoming

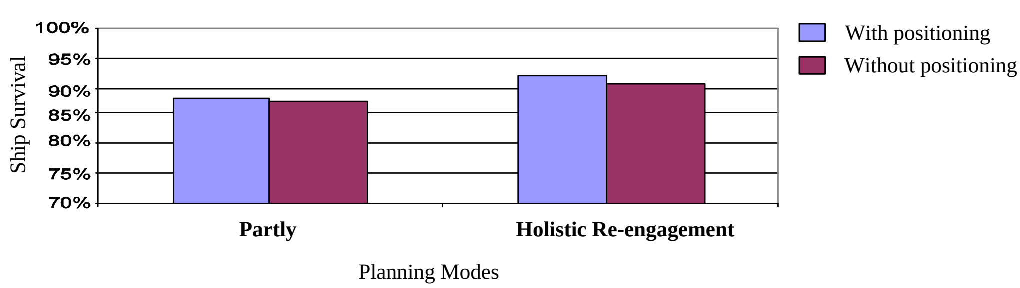


Figure 18: *Results with and without ship positioning using both Partly and Holistic planning modes*

threats in these sectors and improve the defence success.

(a) Standard deviation under the Partly mode for the 6 sectors: 2.89.

(b) Standard deviation under the Holistic Re-engagement mode for the 6 sectors: 3.60.

It can be noticed that the Holistic Re-engagement defence planning mode has a higher standard deviation than the Partly mode. So this factor helps the Holistic Re-engagement mode to improve the success of defence of the ship by re-positioning itself.

6 Multi-ship combat power coordination

The focus, in decision support R&D activities, has so far been on single ship operations[12], with as a main objective the development of a Decision Support System (DSS) that can be integrated into the ship's Command and Control System (CCS) to assist operators in conducting the tactical planning process, focusing on Anti-Air Warfare (AAW). However, single ships are becoming more and more restricted in the actions they can undertake because of the increasing variety and complexity of the situations they will have to handle. This makes them more vulnerable. This restriction can take different forms: the ship resource/human capabilities, the endurance, the reliability, etc. Therefore, to provide an extended capability and higher endurance and reliability, naval forces are more and more often organized into operational groupings for specific missions or tasks. This defines the concept of a Task Group that is becoming the norm in today's naval operations. A Task Group is formed by two or more ships[13], supported by aircraft, helicopters, and/or submarines. The exact size, composition and capability of such a group depend of mission, country, and the situation.

The majority of work on this project was oriented toward issues of coordination of combat power management processes on a single platform. The obvious extension of the problem is to consider issues of coordination of Combat Power Management (CPM) processes for multiple platforms. It is not obvious that the solutions found for a single platform are workable, or even desirable, between multiple platforms. A comprehensive analysis and investigation of this problem is beyond the scope of this project. However, it was useful to give some consideration to this problem.

6.1 Inter-ship coordination

Each participating unit within the Task Group has sets of problems to be solved (target detection, threat evaluation, response planning and execution, navigation). These problems can be solved using several techniques and tools. However, the execution of a given plan by a given unit in the Task Group can jeopardize the safety of the other units, or at least, prevent the execution of their own plans. Therefore, each unit commander has to find agreements with the others for a solution from the set of possible alternatives that satisfy his sub-problem. This defines the "inter-ship coordination" problem.

Similar problems to those of single-ship cases also encountered in Task Group configurations:

1. re-enforce positive interactions;
2. reduce negative interactions;
3. exploit synergy;
4. blind zone reduction;

[12] Also referred to as "point defence" operations.
[13] *E.g.*, destroyers, frigates.

5. Radar Cross-Section (RCS) reduction;
6. Softkill strategy.

Furthermore, new problems arise which are specific to the multi-platform configuration.

1. **Pairing** – This concerns the problem of selecting[14] which platform should engage which threat (Figures 19 (a) and (b)). Such coordination is required to avoid unnecessary redundant engagements of the same threat by several platforms, while other threats might not be engaged at all. This coordination is not aimed at preventing multiple engagements on the same threat, but at making them happen synergically should they become necessary. On Figures 19 (a) and (b), circles refer to the coverage of the ships weapons suite. The sectors at the back of the ship represent blind zones.

   Figure 19 (a) shows the initial configuration of the ships, with two targets being non-engageable (within blind zones of all ships). Figure 19 (b) shows the same situation after the ships have been dynamically re-positioned to bring all targets outside the blind zones.

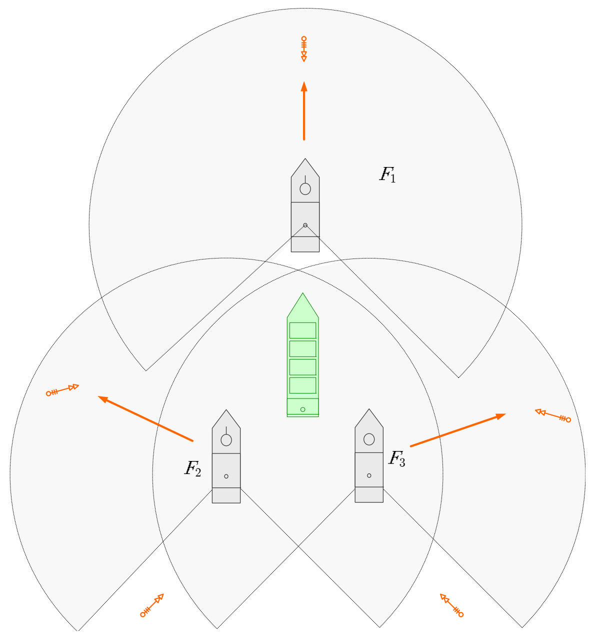
2. **Ship relative positioning** – Given the current emphasis on littoral warfare operations, one important problem that faces the Task Group is the defence screen formation. This refers to the initial relative positions of the different ships for the area defence purposes (Figure 19 (a)), as well as the dynamic repositioning during the operations to maintain safety within the defended area (Figure 19 (b)).

3. **Safety** – Besides the blind zone constraints, the firing capability of the different weapons may be seriously restricted by the presence of the other ships of the Task Group within the theatre of operations. While inappropriate engagements with HK weapons can damage the other participating ships by direct impact, the use of SK weapons may be fatal as well. Indeed, in a tentative to pull a threat off from itself (using the Jamming, the Chaff, or both), a ship can attract the same threat toward another ship[15], which becomes the intended target. Therefore, even though the Task Group offers a higher firing power over a single ship, it is clear that it operates in a more constrained environment, requiring a higher level of coordination.

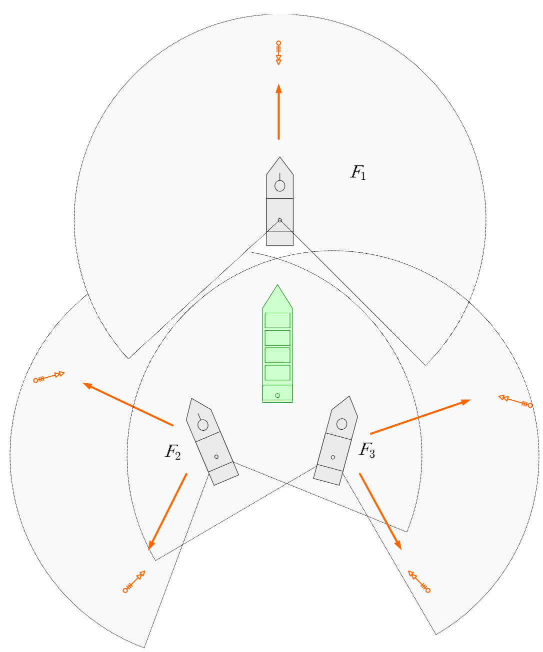
4. **Communication** – Another aspect that makes the inter-ship coordination problem more constrained than the intra-ship one, is the communication aspect. Due to the limited available bandwidth and to the security requirements, the amount and type of data that can be exchanged by the ships is often very limited. This acts as an additional constraint, since the communication is a key element in any (geographically distributed) coordination process. The problem of planning and coordination under a limited bandwidth is addressed in the next section using the mobile agent approach.

[14]This shall be done in decentralized manner, since no platform has the required authority to play the coordinator role.

[15]Or even worse toward the High Value Unit (HVU).



(a) No Coordination



(b) Positioning-based Coordination

Figure 19: *Task Group coordination*

6.2 Communication

To coordinate between multiple platforms, we considered mobile agent technology rather than a "classic" approach. The mobile-agent paradigm consists of small programs that may be dispatched from a local computer and transported to a remote computer for execution. There are several motivations for using the mobile agent approach:

1. Reduction of network traffic – In a classic communication-based approach, there are usually several information flows between platform computers to perform even a simple task.

2. Asynchronous interaction – The local computer sends its agent to a remote computer to perform several tasks, and only when the agent finishes does it retract back to the local computer. A connection does not need to be maintained during the task achievement.

Figure 20 illustrates a situation where coordinating resource management among multiple platforms would provide an advantage.

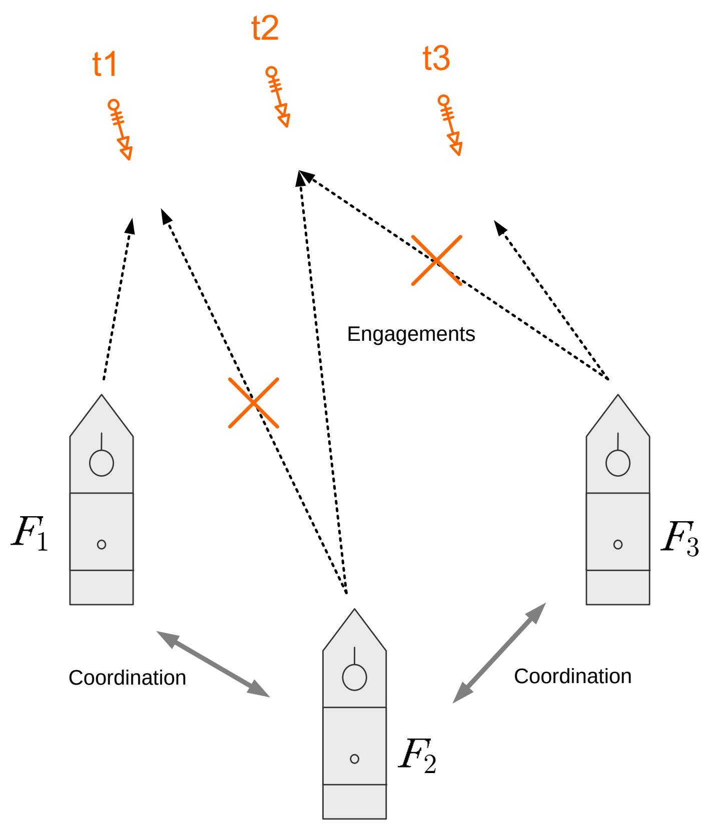


Figure 20: *Coordinated resource allocation among three platforms*

Shown are all the potential engagements of threats as planned independently by the ships. Assuming there is no need to have more than a single engagement of a threat, Task Group

resources can be conserved, with no loss of coverage, by eliminating the engagements indicated by the red circled-x symbol. This could be implemented only by having the different ships coordinate the engagements with each other.

Figures 21 and 22 present the communication layout of the classic and the mobile-agent approaches, where c_{ij} represents the communication flow that sends data from ship F_i to ship F_j.

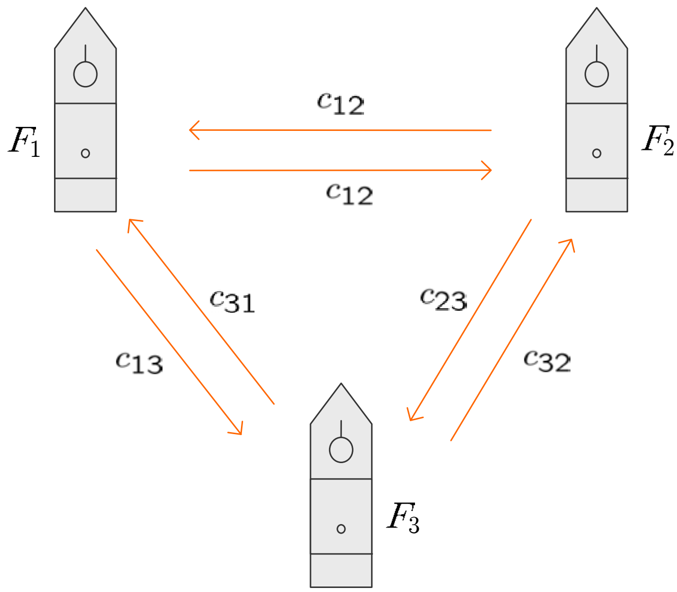


Figure 21: *Classic approach to coordination between platforms*

In the classic approach, each single ship has to coordinate its planning by estimating any potential conflicts with other ships and has to remove conflicts by communicating their conciliation intentions to the others. Therefore, a ship has to send its initial plan to others to let them know its intention, and for each conflict found it has to negotiate a compromise. Having settled conflicts, the ship has to send the new plan to indicate its new intentions to others, and begin again if needed to eliminate every conflict in the global plan. In this way, considerable bandwidth will be needed since at least part of a plan will be exchanged on each communication flow.

However, in the mobile-agent approach, the coordination is done locally, which will reduce the overall communication flow. One way to use the mobile agent approach for coordination is as follows:

1. Each ship creates an initial plan to defend itself.

2. Ships agree on a “meeting place”, for example the lead ship, as F_1 in Figure 22.

3. Each ship creates a mobile agent, whose purpose is to coordinate the actions of the initial plan with the actions of the other ships.

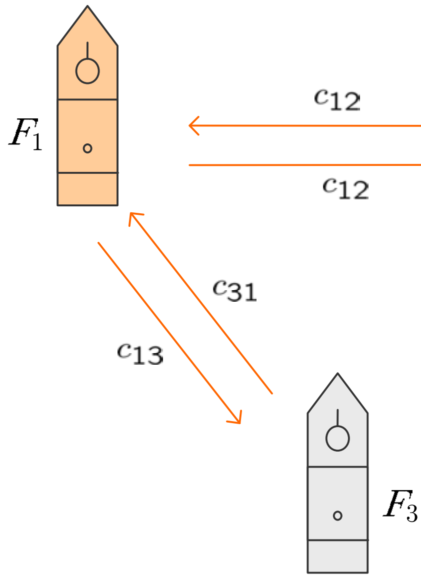


Figure 22: *Mobile-agent approach to coordination between platforms*

4. Ships send their mobile agents to the meeting place, *i.e.*, F_1 in this example.

5. Mobile agents coordinate their defence actions, and when finished, bring back the coordinated plan to the source ships. Figure 22 illustrates this process.

6. When the execution time arrives, if it is available, every ship uses the coordinated plan; otherwise it takes its initial plan.

Figure 23 presents, through the example of Figure 22, the details of the coordination process of the defence actions by the mobile agents.

1. When the mobile agents arrive at the host platform, they are going to send their plans to a coordinator agent. This is designated as step (1) in Figure 23. This agent is not mobile, and it will have the responsibility to track down possible conflicts between the defence actions of the ships. In this way, responsibilities and the sizes of the mobile agents can be reduced.

2. In this example, ships 2 and 3, respectively represented by the agents MobileAg2 and MobileAg3, are in conflict because they both launched a missile on the same threat. Coordinator agent on the host platform is going to track down this conflict, and will ask concerned agents to resolve it. This is designated as step (2) in Figure 23. At the same time, the coordinator agent will also send an initial solution to help the concerned agents to resolve the conflict. It can also force them to take the proposed solution if the agents are unable to resolve the conflict, and if the concerned agents fall under its responsibility, as in a military hierarchy.

3. The agents MobileAg2 and MobileAg3 have to resolve together their conflict in a specified time or use the solution proposed by the coordinator agent of the host platform. This is designated as step (3) in Figure 23.

4. Finally, after the solution to the conflict has been decided, the mobile agents will send the result of their agreement to the coordination agent. This is designated as step (4) in Figure 23.

5. This process will be repeated until all conflicts are examined, or until the time that the agents have to return the coordinated plan to their source platforms arrives.

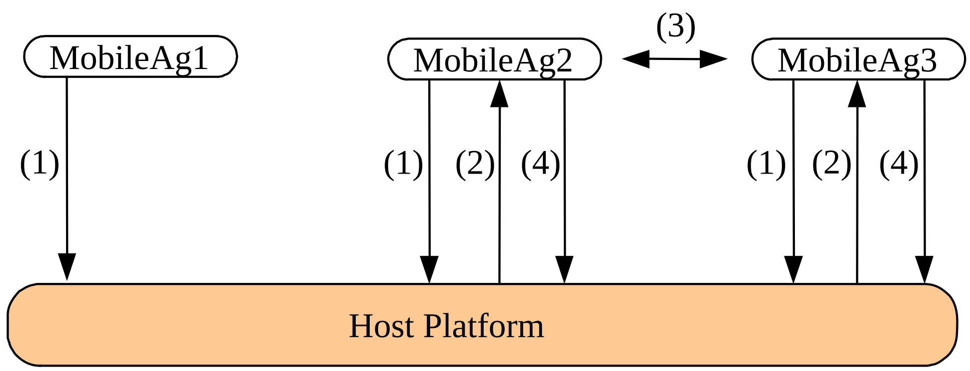


Figure 23: *Mobile agents coordinate their defence plan*

Furthermore, if a new situation occurs, the result or the current planning is likely of no more interest or use, so ships do not have to retract their mobile agents. Each ship will send a message to terminate their current mobile agent and will create a new one to coordinate a plan according to the new situation.

For an experiment with the preceding example, Figure 24 presents the data sent by both the classic and the mobile-agent approaches used to coordinate the ships. The data sent are accumulated over the same total time interval used in previous studies of the survivability of a ship, *i.e.*, up to the point in time where the last threat could impact the ship. In this instance, the total of data sent is the most demonstrative metric. However, it is also safe to say that in general, reducing the data sent (without compromising the information needed for the planning, of course) is also likely to increase the speed, timeliness, and optimisation of planning, and thereby increase the likelihood of ship survivability.

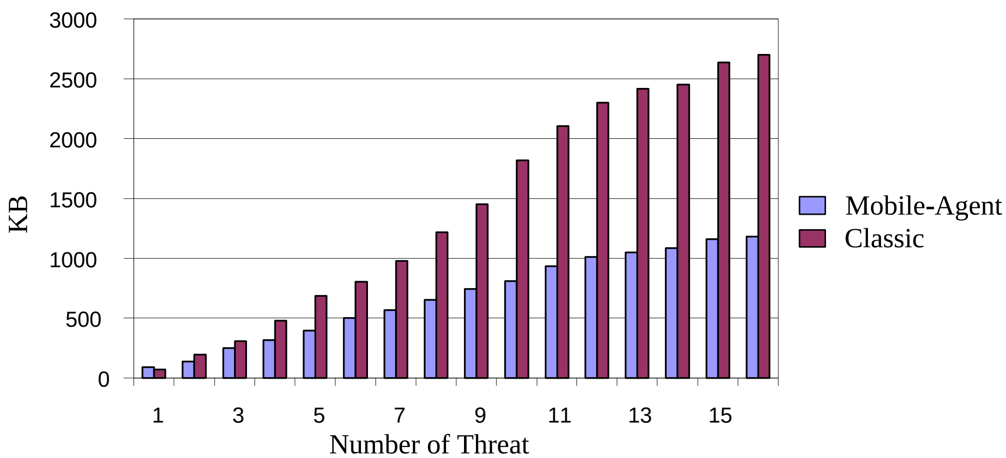


Figure 24: *Volume of data sent with both classic and mobile-agent approaches*

7 Conclusion

The work presented in this document contributes to the effort of acquiring knowledge and expertise in the use of multi-agent planning & coordination, Decision Support Systems (DSS), and agent technology for naval Combat Power Management (CPM). It also allowed the investigation of multi-agent approaches for shipboard CPM that can be integrated into a warship's Command and Control System (CCS) to assist operators in conducting the tactical C2 process, focusing on Above Water Warfare (AWW). Planning with multi-agent systems has been studied in this project with the main objective of conceiving combat power allocation and coordination capabilities for a generic warship that could ultimately be extended to the Halifax Class Frigate and its successors. This report focuses on the resource coordination problem, while allocation algorithms are discussed in the companion report [2].

First, coordination in distributed planning context was presented. The role of coordination of AAW hardkill (HK) and softkill (SK) weapon systems was then examined. An investigation was made into potential coordination techniques that would be applicable to both HK and SK. The different interactions that could occur between these shipboard resources were modeled and presented. Then three different coordination techniques that could be potentially effective for this application were presented. These include i) Central Coordinator, ii) Hardkill agent as a coordinator, and iii) Partial Global Planning. It is concluded that the Central Coordinator technique was better for the Partly and Holistic modes. Having the fewest system support requirements (*i.e.*, minimal communication and bandwidth constraints), the Central Coordinator technique was deemed the most straightforward to implement, and the one most likely able to simply and quickly achieve the fast and effective performance required for C2 decision aids.

Also, since the effectiveness of a particular weapon varies depending on the orientation of the ship with respect to the threats faced, a key element of the coordination process is to manoeuvre the ship to most effectively use all the weapons available. It was shown that the environment surrounding the ship could be divided into fundamental sectors for weapon engagement. A method to determine the general effectiveness of each sector for the threats faced was described. A naïve Bayesian approach that determines the optimal positioning of the ship to most effectively use the HK and SK weapons was presented. Using the two different types of planners for both HK and SK weapon systems, it was demonstrated that using this approach for the manoeuvres augments the ship defence efficiency.

The project investigated several different agent coordination techniques, but for reasons described in this report, implementation concentrated on the Central Coordinator method. However, alternative techniques may still be worth pursuing. To attempt to implement trial applications using these techniques, it may be necessary to move beyond the rapid prototyping environment used in this project (which may not support the communication and bandwidth requirements of these techniques within the performance levels demanded by intended HK/SK application).

Although some initial investigation of coordination with multiple platforms was performed

in this project, more extensive and complete research into this problem is left as future effort. It will be important to determine whether there should be a single overall center for planning all combat resources for all the platforms, or coordination among independent planning sub-components.

Note that only AAW HK and SK weapons were considered in this project. The solutions presented have endeavoured to accommodate within their general architecture future expansion to include other weapon systems[16], but no explicit implementation of these weapon systems was performed. Of necessity, the weapon specifications and threat scenarios used in this project were quite simple. To lend greater credibility and usefulness to the results, it would be beneficial to apply more complex weapon and threat models and more complicated threat scenarios. For example, the threat scenarios used for this project all had Closest Point of Approach (CPA) equal to zero with respect to the ship, which effectively minimizes the value of the Holistic planners. Realistic scenarios would not have all threats with 0 CPA. These changes would necessitate appropriate modifications and upgrades to the rapid prototyping test bed used for this project.

[16] *E.g.*, Anti-Surface Warfare(ASuW) and Anti-Submarine Warfare (ASW).

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Acronyms

AAW	Anti Air Warfare
AWW	Above Water Warfare
ACL	Agent Communication Language
AI	Artificial Intelligence
ASM	Anti-Ship Missile
ASuW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
BDI	Belief Desire Intention
C^2	Command & Control
CCS	Command & Control System
CIWS	Close-In Weapon System
CO	Commanding Officer
CP	Combat Power
CPA	Closest Point of Approach
CPM	Combat Power Management
CPU	Central Processor Unit
CSP	Constraint Satisfaction Problem
CWI	Continuous Wave Illuminator
DAI	Distributed Artificial Intelligence
DAMAS	Dialogue, Agents, Multi-AgentS
DND	Department of National Defence
DPS	Distributed Problem Solving
DR	Damage Reduction
DRDC	Defence Research & Development Canada
DSS	Decision Support System
EA	Electronic Attack
ECM	Electronic Counter-Measures
EM	Electromagnetic
ESM	Electronic Support Measures
EW	Electronic Warfare
EWCP	Electronic Warfare Control Processor
FCR	Fire Control Radar
GMVLS	Guided Missile Vertical Launch System
GUI	Graphical User Interface
GWS	Gun Weapon System
HCI	Human-Computer Interface
HK	Hardkill
HVU	High Value Unit
ICL	Inter-Agent Communication Language
ID	Identity
IFF	Identification Friend or Foe

IR	Infrared
IRST	Infrared Search and Track
KA	Kill Assessment
KQML	Knowledge Query and Manipulation Language
LM Canada	Lockheed Martin Canada
MAP	Maximum A Posteriori
MAS	Multi-Agent System
MCG	Medium Caliber Gun
MLO	Meta-Level Organization
MSDF	Multi Source Data Fusion
NCPM	Naval Combat Power Management
NDS	Naval Display Simulator
NP	Nondeterministic Polynomial
NSERC	Natural Sciences and Engineering Research Council
OAA	Open Agent Architecture
ORO	Operations Room Officer
PGP	Partial Global Planning
PK	Probability of Kill
PP	Partly Planner
Ps	Probability of Success
RAMSES	Reprogrammable Advanced Multi-mode Shipboard Electronic Counter Measures System
RCS	Radar Cross-Section
RCSR	Radar Cross-Section Reduction
RDDC	Recherche et développement pour la défense Canada
RF	Radio Frequency
RM	Resource Management
ROE	Rules of Engagement
SAM	Surface-to-Air Missile
SCSC	Single Class Surface Combatant
SK	Softkill
SRTE	Simulated Real Time Environment
STA	Situation and Threat Assessment
STIR	Separate Tracking and Illuminating Radar
TOF	Time Of Flight
UI	User Interface
UML	Unified Modeling Language
VLSS	Vertically Launched Sea Sparrow
VOI	Volume of Interest

Annex A: Tactical shipboard combat resources

The present Halifax Class Frigate design provides for a layered response to threats.

The Surface-to-Air Missile (SAM) system operates first for targets at medium to long range while the other two systems take over at closer ranges, first the 57 mm Gun then the Close-In Weapon System (CIWS). The Halifax Class Frigate weapon system also includes softkill (SK) capabilities, such as decoy and Jamming systems. Note that only Anti-Air Warfare (AAW) resources are discussed in this annex.

Figure A.1: *Halifax Class Frigate*

The Frigate's hardkill (HK) weapons (SAMs, Gun, CIWS) are used in conjunction with specialized radars used to aim and/or guide weapons to targets. The SAMs and Intermediate Range Gun (IRG) are supported by a Separate Tracking and Illuminating Radar (STIR), and the CIWS is supported by the CIWS radar.

The exact nature of the specifications and capabilities of the various AAW HK and SK weapons on the Halifax Class Frigate is obviously very complex, and much of that information is classified. In order to avoid the procedural complications of using classified information, and to maintain emphasis on the allocation and coordination techniques and not be burdened by the complexity and fidelity of the representation of HK and SK weapons, a considerably simplified model of the relevant weapons was used. This model is a simple, unclassified version of AAW weapons for the Halifax Class Frigate, but does preserve the fundamental features of these weapons. This "generic" frigate thereby becomes the basis for the investigations conducted in this project. The details of the model for HK and SK are provided below.

A.1 Surface-to-air missile (SAM)

Presently, the primary weapon against air threats is the Vertically Launched Sea Sparrow (VLSS). The Halifax Class Frigate's Sea Sparrow is capable of intercepting medium range airborne targets (and horizon range surface targets), thanks to eight vertically mounted twin-canister launchers for Surface-to-Air Missile (SAM) engagement of hostile targets. There are eight Mk 48 launchers port and starboard.

Position on the ship : The SAM is, for simplicity, considered to be positioned at the centre of the ship $(x, y, z) = (0, 0, 0)$. In subsequent work, a position that reflects its actual emplacement on the ship will be considered.

Blind zone: It is assumed that the SAM has no blind zone for launching, but the blind zone of the associated STIR will affect the engagement space.

Kill Probability (PK): When the target falls within the missile's effective range, the probability of kill for a SAM is assumed constant (set at 65%). In the first phase, and for simplicity, this will be assumed independent of target position. Later, the target position could be taken into consideration, and the kill probability will be redefined as a function of the target position with respect to the ship position.

Range: The range of the SAM is about 10 nautical miles. For simulation purposes, it will be assumed a maximum range $R_m^+ = 16$ km and a minimum range $R_m^- = 1.5$ km. These ranges are assumed constant for any bearing or elevation.

Speed : The SAM is assumed to travel following a ballistic (straight line) trajectory at the constant speed Mach .9 ($\equiv\ 0.34 \times 0.9$ km/sec).

Unit Cost: A cost C_m per missile is assumed.

Launcher : There are eight Mk 48 launchers port and starboard. It is assumed that there are 16 SAMs, all initially loaded, and no replacements are available. There will be no delay between the time when the fire order is issued and that when the missile is launched. This assumption may be reconsidered in a later phase.

Guidance System: The Sea Sparrow is a semi-actively guided missile that homes in on targets illuminated by the Continuous Wave Illuminator (CWI) radar that is associated with the STIR.

Fire Control : At least one STIR fire control radar must be operational and the threatening targets must not fall within STIR's blind zone for Sea Sparrow interception to be feasible. A SAM can be fired only after a STIR has locked on the target. Provided STIR acquisition has been achieved, the SAM system addresses only targets at medium ranges.

A.1.1 Constraints and consequences

Given the characteristics of the weapons and the parameters of the scenario, different constraints and information will be required.

1. **Maximum Interception Range:** A target is detected and being tracked by the search radars beyond the maximum range of the STIR. The STIR is cued by a search radar immediately at its maximum range R^+_{STIR}, and it begins its search without delay. Assume that the STIR will take t_{sl} seconds to acquire and lock-on the target. If a SAM is fired as soon as lock is obtained, the following equation gives the maximum range R^+ at which the interception will occur.

$$\begin{aligned} R^+ &= \left[R^+_{STIR} - V_t \times t_{sl}\right] \times \frac{V_m}{V_m + V_t} \\ &= (50.0 - 0.85 \times 3.0) \times \frac{0.34 \times 0.9}{0.85 + 0.34 \times 0.9} \\ &= 12.6 \text{ km} \end{aligned} \tag{A.1}$$

Where:

- R^+: the maximum range to intercept target
- R^+_{STIR}: the maximum range of the STIR (assumed = 50.0 km)
- V_t: the target speed (assumed = 0.85 km/s)
- t_{sl}: the STIR search and lock-on time (assumed = 3.0 s)
- V_m: speed of SAM (assumed = Mach 0.9 = 0.34 × 0.9 km/s)

2. **Maximum Target Speed (V_t^+):** A special case of the previous calculation is when $R^+ = R^-_m$. This corresponds to the maximum of the speed of the target that the SAM can intercept. This is entirely defined by the properties of the STIR.

$$V_t^+ = \frac{(R^+_{STIR} - R^-_m) \times V_m}{R^-_m + V_m \times t_{sl}} \tag{A.2}$$

where R^-_m is the minimum range of the missile (assumed = 1.5 km)

A.2 57 mm Gun

The Bofors SAK 57 L/70 Mk 2 Gun Weapon System (GWS) is an unmanned, all-purpose, rapid-fire Medium Caliber Gun (MCG) that can engage both aircraft and anti-ship missiles at close range. It is a 57 mm caliber gun that is very effective against surface targets out to horizon range, although it is usually used closer in.

Position on the ship: For simplicity, the gun is considered to be positioned at the centre of the ship $(x, y, z) = (0, 0, 0)$. In future versions, a position that reflects its actual emplacement on the ship will be considered.

Range: a maximum range of 5.0 km and a minimum range of $0.9km$ are assumed.

Rate of Fire: The gun is capable to fire up to 200 rounds/min. These can be fired either in a single shot or in burst mode (n_s). The gun can fire consecutive salvos. The only constraint is that a Kill Assessment (KA) must be performed for each salvo, and will take place after the last round in a salvo reaches the point of interception with the

target. Also, in the case of firing several consecutive salvos, allow for the possibility of reassigning the associated STIR (and issuing a cease fire order if it is not too late) based on a kill observation from one of the intermediate KAs before the last round in the last salvo has reached the point of interception with the target. The gun fires in salvos that can be set to 1 to 10 rounds[17]. After every 30 shots (*i.e.*, two 15 round magazines), it takes 5 s to reload the magazines, but the magazines can be reloaded anytime there are 7 rounds or fewer remaining (note that none of the remaining rounds are lost in the reloading process – fired rounds are just replaced). The total number of rounds available in one load of the gun is 150; the gun can be completely reloaded (*i.e.*, providing another 150 rounds) in 8 minutes, with a total of 750 rounds available at the start of the mission. However, these capabilities are further simplified in the implementation of the different planning algorithms according to:

1. The gun fires only with a salvo length of 5 rounds.
2. The gun can fire consecutive salvos.
3. The salvo will not be fired, if there is not enough time to fire <u>all</u> rounds in a salvo.
4. Schedule of a KA for each salvo is established, which takes place after the last round in a salvo reaches the point of interception with the target.
5. A contingency plan for reassigning the associated STIR (and issuing a cease-fire order if it is not too late) is allowed in the case of firing several consecutive salvos. This is based on a kill observation from one of the intermediate KAs before the last round in the last salvo has reached the point of interception with the target.

   Note that, in this context, it is possible to fire several consecutive salvos without waiting to confirm KA from a prior salvo before firing the next. This is a slight relaxation of shoot-look-shoot doctrine.
6. The reloading time for the gun is 0 s, and can take place in mid-engagement.

   Note that performing a complete reload of the gun is ignored, since given the specifications of threat generation, scenarios will last much less than the required 8 minute reload time. Consequently, there is an effective limit of 150 gun rounds available.

Muzzle Velocity: The gun rounds travel following a ballistic (straight line) trajectory at the constant speed of $V_g = 850$ m/s.

Training rate: For simplicity, the slew time to move the gun into position to fire at the target is assumed null. In future more sophisticated version of the scenario a training rate of $50°$/s will be considered.

Magazine Capacity: The total number of rounds available for the gun is 500 rounds (one minute of continuous firing).

Unit Cost: A cost C_g per round is assumed.

[17] It is assumed here that consecutive salvos can be fired with no delay between them.

Launcher: There are four ammunition racks in the Gun turret, each with 32 rounds. It is assumed that there is no delay between the time the fire order is issued, and the gun starts shooting.

Blind Zone: Since there is only one intermediate range gun placed in the front of the ship, it has a blind zone of ±35° in azimuth looking in the backward direction. To this blind zone, one must add the blind zones imposed by the allotted STIR.

Kill Probability: It will be assumed that the probability of kill for the gun is $P_{K_R} = 0.04$/round. As for the simplicity, it is assumed constant and independent of target position, as long as this one is within the gun effective range. In a future version, the PK will be redefined as a three-phase (increasing, constant, or decreasing) function of the distance between the target and the ownship. The probability of kill $P_{K_{NR}}$, when the maximum number possible of rounds $N_{R_{max}}$ is fired at a threat, is given by:

$$P_{K_{NR}} = 1 - \left[1 - P_{K_R}\right]^{N_{R_{max}}} \tag{A.3}$$

Fire Control: The Gun and SAM share the same Fire Control Radars (FCR). The STIRs must be operational for the MCG to be guided and the gun can be fired only after a STIR has locked on the target.

A.2.1 Constraints and consequences

As in the case of the SAM, the characteristics of the MCG weapons and the parameters of the scenario impose different constraints.

1. **Maximum Intercept Range:** A target is detected and being tracked by the search radars beyond the maximum range of the STIR. The STIR is cued by a search radar immediately at its maximum range R^+_{STIR}, and it begins its search without delay. Assume that the STIR will take t_{sl} seconds to acquire and lock on the target. If the gun is fired as soon as lock is obtained, the following equation gives the maximum range R^+ at which the interception will occur.

$$\begin{aligned} R^+ &= \left[R^+_{STIR} - V_t \times t_{sl}\right] \times \frac{V_g}{V_g + V_t} \qquad \text{(A.4)} \\ &= (50 - 0.85 \times 3.0) \times \frac{0.85}{0.85 + 0.85} \\ &= 23.77 \text{ km} \end{aligned}$$

   Where:

   - R^+: the maximum range to intercept target
   - R^+_{STIR}: the maximum range of the STIR
   - V_t: the target speed
   - t_{sl}: the STIR search and lock-on time

- V_g: speed of the Gun round (assumed = 0.85 km/s)

2. **Maximum Duration of Firing:**

$$\begin{aligned} D_{F^+} &= \frac{R_{GUN^+}}{GUN_s} + \frac{R_{GUN^+} - R_{GUN^-}}{T_s} - \frac{R_{GUN^-}}{GUN_s} \\ &= \frac{5.0}{0.85} + \frac{5.0 - 0.9}{0.85} - \frac{0.9}{0.85} \\ &= 9.65 \text{ s} \end{aligned} \tag{A.5}$$

Where D_{F^+} is the maximum duration of firing, R_{GUN^+} is the maximum range of the Gun, and R_{GUN^-} its minimum range. Note that:

(a) R_{GUN^+}/GUN_s is the lead time.

(b) $(R_{GUN^+} - R_{GUN^-})/T_s$ is the flight time of the threat while in the range of gun.

(c) R_{GUN^-}/GUN_s is the time for weapon to reach minimum weapon range.

The time to fire a complete magazine of 30 rounds is

$$30/(200/60) = 9.0 \text{ s}$$

with a maximum of only 9.65 s for firing. After firing 30 rounds the time remaining (0.65 s) is less than the $5s$ required to reload the Gun magazines. Consequently, a maximum of 30 rounds can be fired at a target by the Gun.

Finally, the probability of kill per round (P_{K_R}) is chosen so that

$$P_{K_{Nmax}} = 1 - \left[1 - P_{K_R}\right]^{Nmax} \tag{A.6}$$

Where $Nmax$ is the maximum number of rounds and $P_{K_{Nmax}}$ is the probability of kill for maximum number of rounds.

A.3 Close-in weapons system (CIWS)

The Phalanx Mk 15 Mod 1, a Close-In Weapon System (CIWS), provides the Canadian Navy ships with a terminal point defence capability. It is a self-contained, search, detect, track, and engage weapon system that can be targeted, based upon the Command and Control System (CCS) input or operated in a fully automatic mode. The CIWS provides an ultra-high fire rate of 20 mm shells that represents a "last chance" protection against Anti-Ship Missiles (ASM), fixed-wing aircraft (and surface targets) that may have penetrated the ship's outer defence systems (at very close range).

Currently, the Phalanx's primary role is mainly considered to be the detection and the automatic engagement of low-level, pop-up ASM attackers. Target kill/survival assessments are an important feedback that can be provided by the CIWS to the whole CCS. Also can be provided to the CCS are track data, considering the fact that the CIWS has its own detection 3-Dimension tracking system and can be fused as another sensor.

Position on the ship: For simplicity, the CIWS is considered to be positioned at the centre of the ship $(x, y, z) = (0, 0, 0)$. In future versions, a position that reflects the actual emplacement of the CIWS on the ship will be considered.

Range: It is assumed a maximum range of 2.5 km and minimum range of 0.0 km.

Speed: The CIWS rounds travel following a ballistic (straight line) trajectory at the constant speed of $V_c = 1200$ m/s.

Rate of Fire: The gun is capable to fire up to 55 rounds/s.

Magazine Capacity: The total number of rounds available for the CIWS is 1500 rounds (*i.e.*, one minute of continuous firing).

Fire Control: The CIWS can be fired only after the CIWS self-contained search and track radar has locked on the target. It will be assumed that the slew time to move the CIWS into position to fire at the target is 0 s and there is no delay between the time the fire order is issued and the CIWS starts shooting.

Blind Zone: Due to its emplacement at rear of the ship, the CIWS suffers from a blind zone of $\pm 15°$ in bearing looking in the forward direction.

Kill Probability: It will be assumed that the probability of kill for the CIWS is $P_{K_R} = 0.006$/round. As for the simplicity, this is assumed constant and independent of target position, as long as the latter is within the CIWS effective range. In a future version the PK will be redefined as a three-phase (increasing, constant, and decreasing) function of the distance between the target and the ownship. The PK when the maximum number possible of rounds $N_{R_{max}}$ is fired at a threat is given by:

$$P_{K_{NR}} = 1 - \Big[- P_{K_R} \Big]^{N_{R_{max}}} \tag{A.7}$$

A.3.1 Constraints and consequences

1. **Maximum Interception Range:** It is assumed that the CIWS FCR starts its search immediately at its maximum range R^+_{CIWS} and that it will take t_{sl} seconds to acquire and lock on the target. If the CIWS is fired as soon as lock is obtained, the following equation gives the maximum range R^+ at which the interception will occur.

$$\begin{aligned} R^+ &= \Big[R^+_{CIWS} - V_t \times t_{sl} \Big] \times \frac{V_c}{V_c + V_t} \\ &= (5.5 - 0.85 \times 1.0) \times \frac{1.2}{0.85 + 1.2} \\ &= 2.7 \text{ km} \end{aligned} \tag{A.8}$$

   Where

   - R^+ : the maximum range to intercept target
   - R^+_{CIWS} : the maximum range of the CIWS fire control radar

- V_t: the target speed
- t_{sl}: the CIWS FCR search and lock-on time
- V_c: speed of the CIWS rounds (assumed = 1.2 km/s)

2. **Maximum Duration of Firing:**

$$\begin{aligned} D_{F^+} &= \frac{R_{CIWS^+}}{CIWS_s} + \frac{R_{CIWS^+} - R_{CIWS^-}}{T_s} - \frac{R_{CIWS^-}}{CIWS_s} \\ &= \frac{2.5}{1.2} + \frac{2.5 - 0.0}{0.85} - \frac{0.0}{1.2} \\ &= 5.0 \text{ sec} \end{aligned} \tag{A.9}$$

Where D_{F^+} is the maximum duration of firing, R_{CIWS^+} is the maximum range of the CIWS and R_{CIWS^-} is its minimum range. Thus, the maximum number of rounds possible is $5 \times 55 = 275$ rounds.

A.4 Separate tracking and illuminating radar (STIR)

The current Halifax Class Frigate combat system comprises two Fire Control Radar (FCR) systems called Separate Tracking and Illuminating Radar (STIR: respectively STIR-A and STIR-B). The STIRs are responsible for the control of the Surface-to-Air Missile (SAM) fire channels and the Medium Caliber Gun (MCG). They provide the SAM and MCG weapon systems with fire control quality track data for engageability and fire control calculations.

The STIR system also provides designation to the Close-In-Weapon-System (CIWS) for targets when it has to engage an air target. Because there are two STIRs (and hence two fire control channels) available, the CPM system can launch either one or a salvo of two missiles against the highest threat target, and then almost immediately the same against the second highest inbound threat. The STIRs provide the capability of tracking air (and surface) target ranges such that all ownship weapons can be launched to intercept their targets at maximum weapon range.

Inputs to STIRs are lock-on target information (position) and commands. Outputs are status reports. Care must be taken to prevent both STIRs from engaging a single threat. Appropriate delays for STIR acquisition before firing must be part of the planning mechanism of combat RM [14]. The main characteristics of the STIRs are as follows.

Position on ownship: For simplicity, both STIRs (STIR-A and STIR-B) are considered positioned at the center of the ship $(x, y, z) = (0, 0, 0)$. In future versions, positions that reflect the actual emplacement of the STIRs on the ship will be considered.

Blind zone of STIR-A: 330 to 30° in azimuth.

Blind zone of STIR-B: 150 to 210° in azimuth.

Range: Each STIR is assumed to have an effective range of 50 km. Both units are assumed to have polar angle ϕ coverage of $0° < \phi < 90°$

Search and lock time: For simplicity, it is assumed to be constant at $t_{sl} = 3$ s. In future versions, the search and lock time will depend upon the quality of the track provided to the STIR by the search radars [14].

Hand-off: Once STIR lock is obtained, control can be passed to the second STIR with presumably no delay (*i.e.*, the second STIR is provided with a precise bearing and elevation in order to begin its search). Note that control is passed to a second STIR only if there is no SAM in-flight (*i.e.*, once a SAM is launched, it must be guided to the target by the same STIR assigned to it at the launching time). STIR must remain illuminating the target during total Time Of Flight (TOF) of SAM to target. If the STIR controls a gun, the STIR can be unlocked at any time, causing the gun to cease fire.

Kill Assessment (KA): It is assumed that the assessment of kill is performed via the STIR for SAM takes a fixed duration of 2.5 s. But it is assumed the KA done via the STIR for the gun takes a fixed duration of 1.0 s.

A.5 Close-in weapons system (CIWS) radar

Unlike the STIR, there is only one unit that is entirely dedicated to CIWS. The time for the CIWS radar to search for and lock on the target is assumed constant and set at 1.0 s. In the autonomous mode of CIWS operation, the CIWS is assumed to independently search for targets, so that there is always a finite search and lock time for the CIWS radar to acquire a target. Note that there is another mode of operation where, if a STIR is locked on a target, the CIWS can be given that precise position to start its search phase. The time to do so is negligible, and it leads to directed firing on a specific target.

The CIWS illuminator can be unlocked at any time, causing the CIWS to cease fire. The KA performed via the CIWS illuminator takes a fixed duration of 1.0 s (but for now, KA for the CIWS will be ignored).

1. **Blind zone:** The same blind zone as the one of the CIWS described in Section A.3, that is $\pm 15°$ in bearing looking in the forward direction. The main CIWS FCR characteristics are given below.

2. **Range:** It is assumed to have a maximum range of 5.5 km and minimum range of 0.0 km.

3. **Estimate of search and lock-on time:** In the autonomous mode of CIWS operation, the time for the CIWS radar to search for and lock on the target is assumed to be constant, set at 2.0 s. When the CIWS radar is cued by the STIR (that provides it with a precise position to begin its search and lock) the time is negligible, then set at 0.0 s.

A.6 Softkill combat resources

The Halifax Class Frigate combat resources also include Electronic Attack (EA) capabilities. EA has the mission to prevent or reduce the enemy's use of electromagnetic (EM) spectrum.

It has, for many years, been called Electronic Counter-Measures (ECM). EA uses EM or directed energy to attack personnel, facilities, or equipment in order to:

1. damage physically the enemy assets by use of high levels of radiated power or directed energy; this is referred to as destructive EA; and
2. make the enemy asset temporarily ineffective but does not destroy it. This is rather a non-destructive EA, also referred to as "soft kill". This form of EA is the only one that will be considered in this project.

The SK weapon suite on the Halifax Class Frigates comprises: a Jammer, decoys (Chaff, sonobuoy, rubber duck), and flare.

A.6.1 Jammer

A Jammer aims at modifying the waves of the radar that controls the Anti-Ship Missile (ASM) that comes toward the ownship. It tries to modify the destination of the ASM by affecting its own radar. There are two primary modes of use for Jamming:

1. Break missile lock on ownship – Assume a 20.0 s duration for the Jammer to search for and acquire the missile threat, and then process to cause the missile to break its radar lock on ownship.
2. Create a false target position on the missile's radar – A jam pulse is used to create a delayed offset from a normal radar reflection, what is interpreted by the missile's radar as the actual target position. Because of the offset, the range determined by the missile's radar is greater than the actual range of the target. Once the Jammer has acquired the missile (*e.g.*, in the break lock mode), this processing happens quickly, say in 3.0 s.

The maximum Jamming range is 25.0 km. The percentage of success for Jamming only (without Chaff) is 40.0% and the percentage of success for Jamming and Chaff together is 80.0%. There are two antennas. One is assumed to see $\pm 100°$ pointing left of ownship, the other $\pm 100°$ pointing right of ownship (*i.e.*, there are regions of overlap, of $20°$ each, between the two antennas: one region is located at the front of the ship, the other at the back). Each antenna can deal with up to two threats. Responsibility for Jamming a threat can be passed from one antenna to the other, provided, of course, that the threat is within the new antenna's coverage region when it is to take over, and that the new antenna is not already dealing with two other threats.

A.6.2 Decoys (Chaff)

A decoy is designed to appear to the enemy seeker, be it operating in Radio-Frequency (RF) or Infra-Red (IR) frequency bands, more like a protected platform than the platform itself. It aims at causing the guided weapon to attack the decoy rather than its intended target, for instance. The difference between decoys and Jammers is that decoys do not interfere

with the sensors tracking them, but rather seek to attract the attention of those sensors causing them either to, acquire it and attack it, or to transfer the tracking focus.

The Chaff bursts constitute the main decoy system against radar-guided threats for the Halifax Class Frigate. Chaff bursts may be used as an expendable distraction or seduction decoys for ship protection against ASMs. In this case, the separation of the decoy from the target is generated only by the movement of the ship and by the wind, which moves the Chaff burst. The Chaff burst is ideally placed in the corner from which it will separate from the ship most rapidly. The burst placement is chosen based on the type of radar in the attacking missile, the relative wind direction and velocity, and the direction from which the attack is coming.

For this project, a maximum Radar Cross-Section (RCS)[18] of 5000 m^2 is assumed for the Chaff. Also, for simplification, it is assumed that the Chaff cloud instantaneously forms a sphere that remains fixed in size for the duration of the cloud. At a later time, one can add time for the cloud to plume, use a more realistic shape for the cloud, and account for degradation, dispersion, and movement of the cloud due to gravity and other environmental effects.

- Deployment range (from ownship): 225 m
- Duration of Chaff: up to 10 min
- Total inventory of Chaff shells: 30
- % of success for Chaff only (no Jamming): 30%
- % of success for Jamming and Chaff together: 80%

In the current Chaff system (SHIELD), target information (position, velocity, etc.), meteorological conditions, and an instruction to deploy Chaff are all input to the system, so the latter determines when and where the Chaff will be deployed. Note that the Chaff will be greatly affected by meteorological conditions, which have not been accounted for in this description.

[18]The RCS is the measure of a target's ability to reflect radar signals in the direction of the radar receiver.

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Annex B: Naval defence simulator (NDS)

A simulator has been developed during this project to allow, through various scenarios, for large amount of tests on the investigated agent- and multi-agent-based planning concepts. The Naval Defence Simulator (NDS) shown on Figure B.1 allows specific tests to be replicated as many times as desired, what is obviously impossible to match on real-life systems. With low costs compared to real-life demonstrations, this allows to develop, implement, validate, and compare a broad range of concepts. Another advantage of having a simulator is that it allows us to focus on particular aspects of the C2 process.

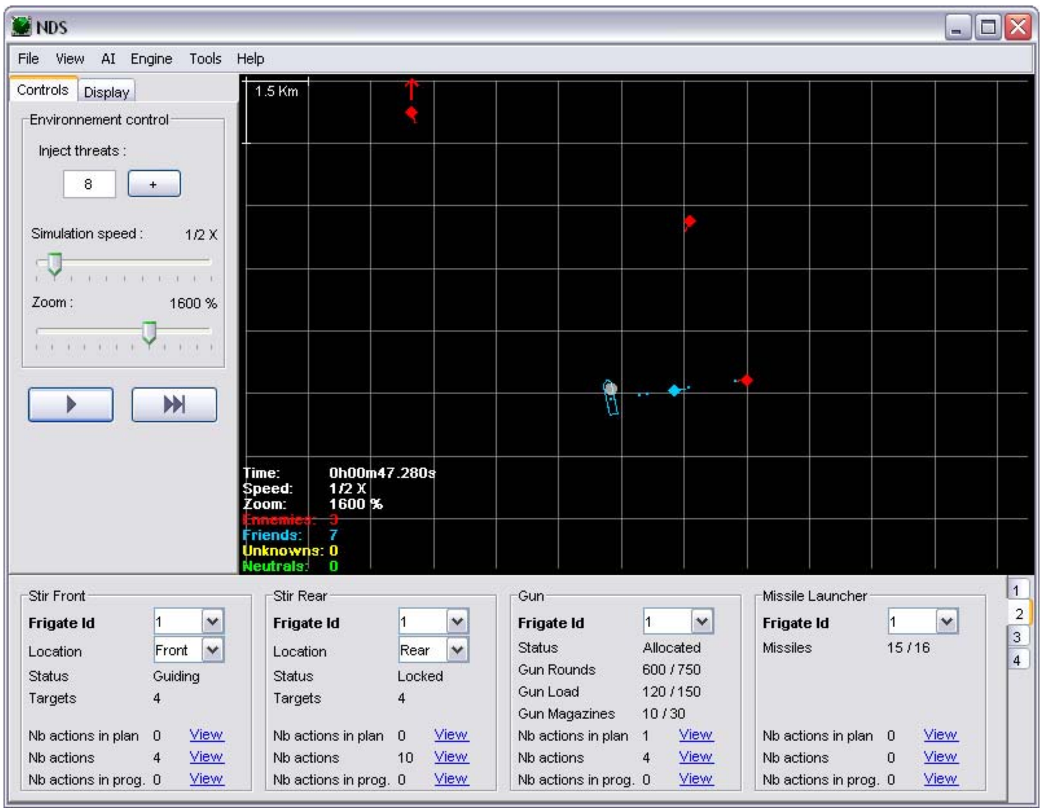


Figure B.1: *Naval Defence Simulator (NDS) view panel*

During the project, the focus has been on resource allocation and coordination, so the problem of situation analysis has not been treated.

B.1 Architecture

The programming language used is Java, because of its ease of use, flexibility, and portability. The NDS is developed in three-tier architecture, as shown on Figure B.2. The first tier, the *Data*, is composed of the simulation objects. The second tier, the *Logic*, is composed of many subsystems and is responsible for the kinetics, time flow, agents, and communications management. When an object needs to be inserted (*e.g.*, when firing a Surface-to-Air

Missile (SAM)) or deleted (*e.g.*, when an Anti-Ship Missile (ASM) has been destroyed), it is the task of the *engine* to evaluate the relevance of the action and take the appropriate steps. The last tier, the *User Interface* (UI), is the medium of interaction between the users and the engine. It is with the Graphical User Interface (GUI) that users create and record scenarios, get a view of the internal values of objects, and start batch tests. The design of the simulator itself makes it easy to deactivate the GUI and use automated test modes.

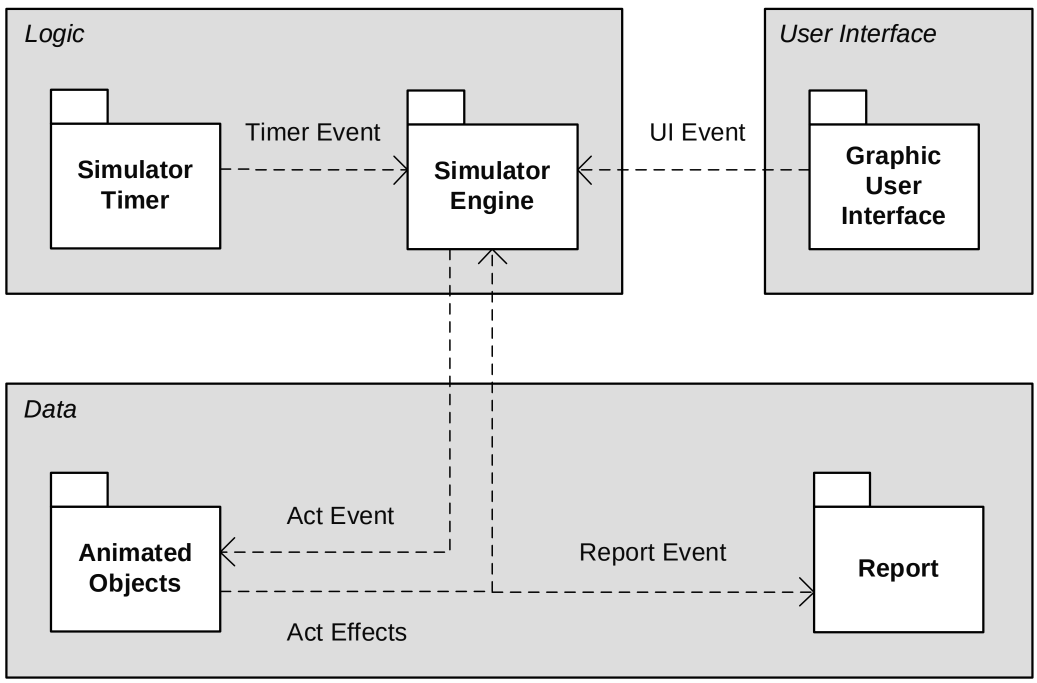


Figure B.2: *Naval Defence Simulator (NDS) architecture*

B.1.1 Time management

Discrete time mechanism is used as a simulation approach. In this structure, every object has the same virtual time to act. The *timer* triggers time events in the engine, which then runs each object for a specific time quantum. Once an object is run by the engine, it acts and deletes impossible actions and moves. After all animated objects have moved, act effects, like collisions, are evaluated and destroyed objects are cleared from the simulation. While acting, objects look for valid actions in their list to execute. The planners, as part of the simulation engine, take the extra step of planning which actions should be executed beforehand. This is illustrated in Figure B.2.

An interesting advantage of this mechanism is that one can easily speed up or slow down the simulation. There are two factors that can be changed: the interval at which time events are sent, and the time quantum in which each object must act. Thus, it is virtually possible to speed up the simulation to hundreds of times faster than real-time, but still can let some part execute in real-time when necessary (as with some anytime algorithms). In fact, when sped up to its maximum value, a typical simulation of 5 minutes lasts less than 1 second

on the computer used to test scenarios. Furthermore, the simulator has been designed in such a way that it is possible to vary the simulation speed while leaving the normal Central Processor Unit (CPU) time to the planning algorithms.

B.1.2 Agent management

In the current version of the simulator, there is one agent for each ship[19] that is responsible for deliberating on the situation of its attributed ship. In the NDS, each object, including agents, act for a specified time quantum during each simulation *round*. The inner control loop of the various agents let them monitor their environment and plan on the evolving situation. Moreover, they can receive messages and react at any time during a simulation to a more complex situation. These messages are received through the *Communication Central*.

B.1.3 Communication management

In Mutli-Agent Systems (MAS), cooperating agents often need to exchange messages. In the NDS, this is done via the *Communication Central*, which receives messages from agents and dispatches them to the correct recipient agents. Mostly, it serves to model communication waves in the simulator environment and accordingly delays the reception of messages by the receiving agents. Three different delays are introduced for each message sent.

- *Message preparation delay* – This is a constant delay, representing the time needed to make the physical communication channel available and add the appropriate headers to the message to be sent.

- *Distance induced delay* – This is the delay induced by the physical distance between sender and receiver. This is derived from the speed of radio waves that is 3.00×10^8 m/s. Therefore, the beginning of a message sent to an ally 3.0 km away will be received 10.0 milliseconds later.

- *Bandwidth induced delay* – This is the delay induced by the total length of the message. By varying this parameter, it is possible to simulate various communication conditions, such as to simulate a stronger encryption, thus reducing the bandwidth and decreasing the total throughput of the system. Even though this is not yet implemented, an appropriate reduction in bandwidth, when Jamming units are used, can be simulated by modeling the background noise of the system.

B.2 Graphical user interface (GUI) panels

On the left side of the Graphical User Interface (GUI), there is a zone with two different panels. The first one is the simulation control panel, which contains elements such as speed and zoom controls. The simulation progress can be entirely controlled from this panel, or

[19] However, it is possible to have more than one agent for each ship. For example, it is possible to use one agent for HK systems and one for SK systems. It is also possible to have specific agents responsible for multi-platform coordination, etc.

also from the engine menu and keyboard shortcuts. In the simulation control panel, a user can:

- add new threats generated at random position,
- start and pause the simulation at any given time,
- zoom in and out between 12.5% and 25,600%,
- speed up or slow down the simulation between $\frac{1}{4}$X and 256X, and
- advance the simulation by exactly one turn, which is equal to 80.0 milliseconds in simulation time.

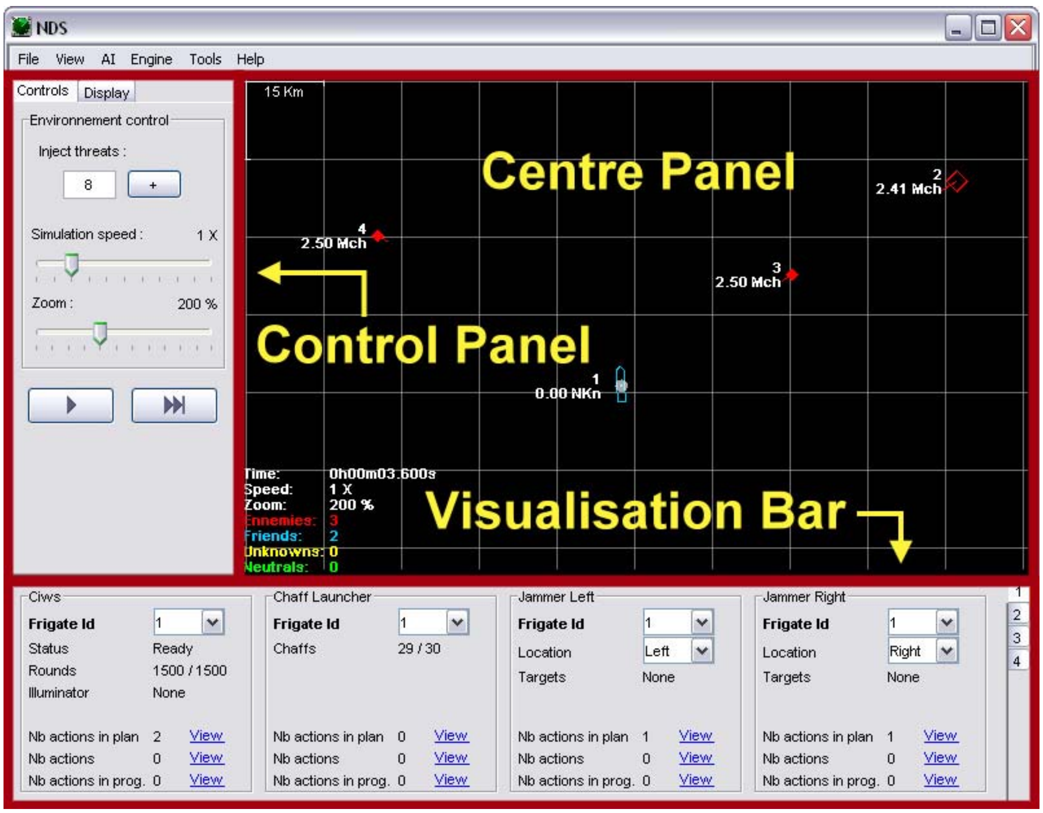


Figure B.3: *Components of the Graphical User Interface (GUI)*

The centre panel of the simulator allows users to follow the development of the current simulation. It uses symbols and colors to visually represent objects. Table B.1 shows the different symbols used in the simulation. The color code (Table B.2) serves to represent the allegiance of the objects.

The following objects, for visibility concerns, derogate from this color code. First, the cargo vessels are represented in white, to further accentuate the fact that they are units with no

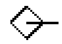
Symbol	Object
	Cargo vessel
	Frigate
	Airplane
	Missile
	Chaff cloud

Table B.1: *Symbols used in Naval Defence Simulator (NDS)*

Color	Allegiance
Blue	Allies
Red	Enemies
Yellow	Unknown
Green	Neutral

Table B.2: *Color codes used in Naval Defence Simulator (NDS)*

actual defensive capability. Second, the Chaff clouds are represented as white circles with alpha blending.

The left zone also contains a second panel that is the simulation display panel. In this panel, the user controls display on the centre panel. There are display options common to most objects and some other options applicable only to specific objects. The elements of the first category allow displaying the unique Identity (ID) of an object, as well as its speed and position. In the centre panel, the Gun and Close-In Weapon System (CIWS) rounds and Chaff clouds will not have their information displayed. The reason for this is that there would be too much information packed in the same space and it would clutter the display with no appreciable added value. On the other side, the elements that are specific to ships allow the user to display simultaneously the coverage range of any onboard system, such as radar and CIWS. Figure B.4 shows the range/blind zone of the Gun as well as the coverage zone of both Jammer units on each side of the ship. Note that areas where both Jammer systems are available are clearer.

The bottom panel of the GUI contains the visualisation bars. There are no real limits on the number of bars that can be present. Each bar is customizable and contains four visualisation items. A right click on any item slot lets the user change what is shown in this slot. The implemented visualisation items are separated in three types, as depicted in Table B.3: systems, objects, and modules.

The first class contains the system items pertaining to the simulator core. The second class of items is the object visualisation items, which present information relative to specific objects and object types. The last visualisation item is specific to NDS and shows the different resource modules of the frigates. It is easy for a developer to create new visualisation types. Moreover, the settings chosen and the displayed visualisation bars are saved when changed

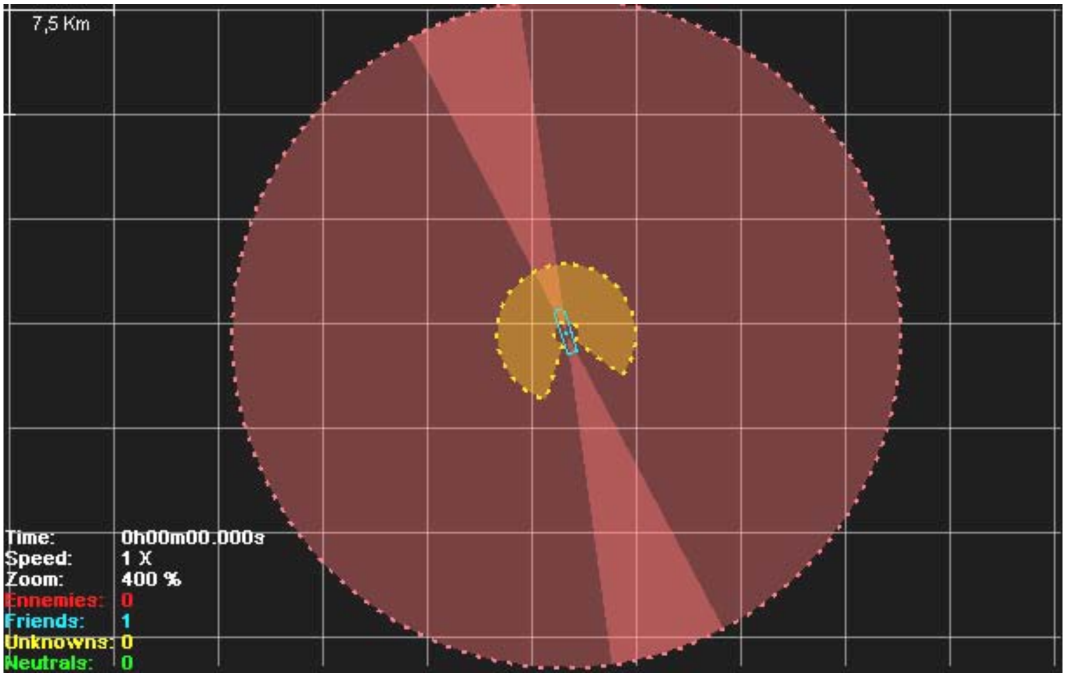


Figure B.4: *Example of system ranges*

System	Objects	Frigate modules
Memory Consumption	Airplane	CIWS
System Information	Missile	Gun
	Frigate	Missile Launcher
	Cargo vessel	Chaff Launcher
		Jammer
		STIR

Table B.3: *Available visualisation items in NDS*

and reloaded when the simulator is launched again. Figure B.5 shows a visualisation bar with four visualisation items (in this case: a *Frigate View Item*, *CIWS View Item*, *Jammer View Item*, and a *Missile View Item* items).

B.3 Debugging

Included for developers is the *debug screen*. This screen, available from various places in the GUI, allows the developer to see the exact content of some specific objects. It lets the programmer see the values of the members of this instance (even private ones) as well as the referenced objects and their contents. An example of this *debug screen* is shown in Figure B.6, where the details of a planned CIWS fire action are given.

In this screen are given the planned time of execution (at 55.11113 s), the hard deadline (at 60.135635 s), the list of preconditions that must be met before firing, etc.

Figure B.5: *Bar of visualisation items*

B.4 Simulation control

When starting the simulator, the file `tests.cfg` is loaded, if it exits. In this file there is a flag used to enable or disable automated testing. If automated testing is enabled, the remainder of the configuration file is used to set the testing environment. If this flag is disabled, the configuration file is left unused and the simulator GUI is launched as usual.

Following are the parameters that permit tailoring the situations to be tested. The parameters marked with an asterisk (∗) are shown in Figure B.7 of the simulation manager template.

Parameter	**Description**
*Maximum duration**	Controls the maximum duration of single scenarios. Even if the scenario is not over (there are still ASMs or airplanes with ASMs left in the simulation) when the maximum time specified is elapsed, the scenario is ended.
*Number of scenarios**	This is the number of scenarios executed for each combination of parameters (planning algorithm, movement algorithm, coordination mechanism, threat number, etc.).
*Number of iterations**	This is the number of iterations performed for each scenario. This means that, for each combination of parameters, the number of tests to be made will be (*Number of scenarios*×*Number of iterations*).
*Min/Max number of threats**	These are the maximum and the minimum numbers of threats that will be present in a scenario. If these two numbers are set to be different, all possible values between the two numbers will be used during scenario generation.
*Planning algorithm**	This is the algorithm used for the planning in the tests. The user can choose either 1) to use a single algorithm or 2) to test with all algorithms. In the case where all algorithms are tested, one combination will be generated for each algorithm available.

*Movement algorithm**	This is the algorithm used for movements in the tests. The user can choose either 1) to use a single algorithm or 2) to test with every algorithm. In the case where every algorithm is tested, one combination will be generated for each algorithm available.
Coordination mechanism	This is the mechanism used for multi-agent coordination in the tests. The user can choose either 1) to use a single mechanism or 2) to test with all mechanisms. In the case where all mechanisms are tested, one combination will be generated for each mechanism available.
Formation	This is the ship formation to test, defining the relative position of each platform in the Task Group. This parameter is used only when a coordination mechanism is tested. A combination will be generated for each formation to test.
Distance	The distance between the ships in a coordination formation. Usually, it represents the distance to the centre (*e.g.*, the protected High Value Unit -HVU- such as the cargo ship) along one axis. This parameter is used only when a coordination mechanism is tested.
Communication preparation delay	It represents the time to correctly prepare a message with security measures and the correct headers. This is invariant and independent of the size of the messages. This parameter is used only when a coordination mechanism is tested.
Bandwidth	This is the bandwidth of the communication channel, and it is fixed for the length of the simulation. Thus, the bandwidth can be reduced to represent background noise or degraded communication conditions. This parameter is used when any coordination mechanism is tested.
Communication waiting time	This represents the time any agent has to deliberate and return a response. When waiting for a reply, an agent will wait a specific time defined by: *Time to send the initial message + Communication waiting time + Estimated time to receive the reply.* This parameter is only used when a coordination mechanism is tested.
Ship per threat	This is the number of ships that will engage each incoming threat. The values of this parameter range from one ship per threat to all ships for each threat.

Allocation algorithm	Some coordination mechanisms (*Central coordination* and ∼*Brown coordination* [15]) compute a matrix of success probability, which contains the evaluation of probability to destroy each threat, for each ship. When this matrix is obtained, two allocation algorithms can be used: a complete state lookup and a greedy algorithm.
Maximum ship weight deviation	The ∼*Brown coordination* uses different ship weighting related to each ship's importance. Once obtained, the weights are normalized in such a way that the maximum weight is 1 and the minimum is (1−*Ship weight deviation*).
Fleet engagement priority evaluation	In the ∼*Brown* method, the priority of each threat according to the fleet is evaluated from the received probabilities of success (P_S) for each ship. These fleet priorities will later be used in the evaluation of the individual priority. There are three different fleet engagement priority evaluations: the mean of P_S, the highest P_S and the multiplication of P_S.
Capability matrix evaluation	In the ∼*Brown* mechanism, a capability matrix is computed by each ship at a certain moment. Many different evaluation methods can be tested.
Backup	This parameter represents whether or not ships will demand backup in case they cannot engage a threat with a sufficient P_S. This is used only in the *Zone Defence* coordination mechanism.
Threshold	Used in the *Zone Defence* coordination method, this represents the P_S threshold under which a ship will seek assistance in the engagement of a threat.
*Number of ships**	Used only in the *Area Defence* coordination mechanism, this is the number of ships in the scenarios to test. It is used to evaluate the effects of more or less defending ships on an AAW scenario. In the other coordination protocols, the defined formation is used with exactly four ships.
*Bayesian sector**	This is the Bayesian sector to be tested. Further details about Bayesian sectors are available in [16] and [17]. This restricts the random appearance of threats in a specific sector (based on the ship that is positioned in the centre of the simulation area). This is a special test that is used only to generate the results of the *Bayesian movement* approach.

*Output**	This is the file where the outputs are saved. Typically, they are saved in Excel format (.xls), though results can also be saved in comma separated values format (.csv).

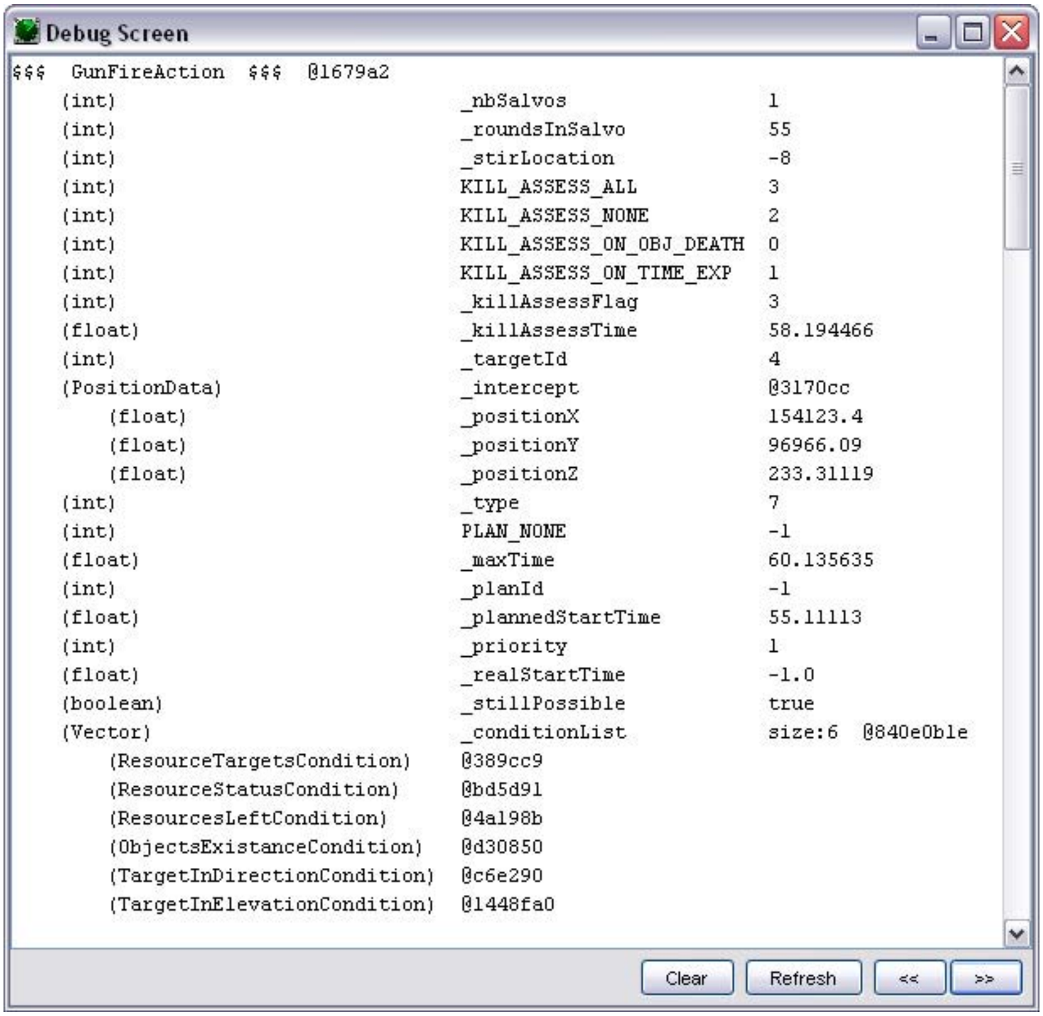


Figure B.6: *Debug screen*

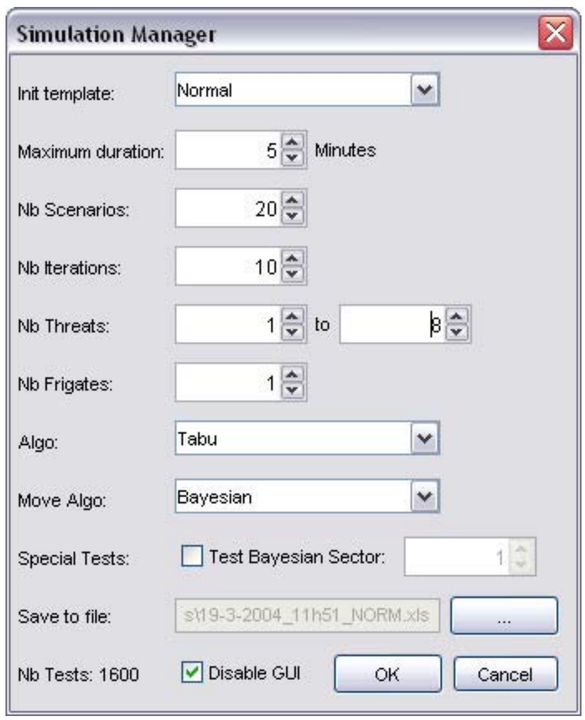


Figure B.7: *Simulation manager panel*

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Reaction times of modern current and future war platforms are eroded, since they are expected to operate in a large variety of complex scenarios. To cope with the increasingly diverse air and surface threats, modern platforms, either operating in a single ship configuration or within a (joint and/or combined) task group/force, will require their sensor suite and weapon arsenal to be efficiently managed. The coordination and tight integration of these resources will also be required.

The Decision Support Systems (DSS) Section, at Defence Research & Development Canada – Valcartier (DRDC Valcartier), has initiated collaboration with industry and university partners. This collaboration aims at developing and demonstrating advanced concepts of combat resource management, which could apply to the current Command & Control Systems (CCSs) of the Halifax and Iroquois Class ships, as well as their possible future upgrade (*e.g.*, Canadian Surface Combatant platform), in order to improve their performance against the predicted future threat. This activity builds upon and broadens the scope of prior research in the domain. It is oriented to the study, development, and implementation of management decision aids for tactical shipboard resources, based on intelligent agent technology and techniques for multi-agent planning and coordination.

This report presents a review of agent and multi-agent coordination approaches. Theoretical basis of distributed planning in multi-agent systems is introduced and coordination mechanisms are described. Multi-agent approaches are used to address the coordination problems for: 1) hardkill/softkill, 2) weapons deployment/ship navigation, and 3) multi-ship positioning and operations. Results of the implementation and test of different algorithms for these combat resource coordination problems, in naval engagements, are presented and discussed.

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